Date:- 18/09/2017

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To,
The registrar,
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Vadodara.

Kind attention:- Dy. Registrar (Academic)

Sub:- Submission of PhD Synopsis-The Title of Thesis : **"Studies on Effect of Welding Parameters on Corrosion and Mechanical behaviour of Duplex Stainless Steel welds".**

Through:- The Guiding Teacher,
The Head, Department of Metallurgical & Materials Engineering
The Dean, Faculty of Technology & Engineering

Sir,
I has registered for PhD in Metallurgical & Materials Engineering. My Registration number is 219 dated 15-09-2010. I am submitting four copies of Synopsis on DT.18-09-2017 I have paid the PhD exam fee of Rs. 7880/- on DT.18-09-2017.
In this connection, kindly do the needful.

Thanking you in anticipation,
Yours Sincerely,

P.K.Nanavati
(Name of Candidate & Signature)

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(Prof.Dr. S.N.Soman)

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Encl:- 1. PhD Synopsis Submission Fee receipt 2. PhD registration Certificate 3. Renewal of Registration (Extension) 4. PhD entrance test (PET) Certificate 5. Course work certificate(Statement of earned credit) 6. Fees receipt of Last Three Years. 7. Charge of Guide

Synopsis of the thesis

Studies on Effect of Welding Parameters on Corrosion and Mechanical Behaviour of Duplex Stainless Steel welds.

Submitted for the award of the degree

Of

DOCTOR OF PHILOSOPHY

In

(Metallurgical and Materials Engineering)

By

P.K.Nanavati

Metallurgy Department

Government Engineering College,

Sector-28.

Gandhinagar

2017

Guide

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Department of Metallurgical and Materials Engineering,

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Introduction.

Duplex stainless steels (DSS) are finding abundant use in the Petrochemicals and refining industry, mainly because they do offer very good economical combination of strength and corrosion resistance in sour service atmosphere.

DSS typically have an annealed structure consists of half ferrite and half austenite, although the ratios can vary from approximately 35/65 to 55/45. (Photo of micro)

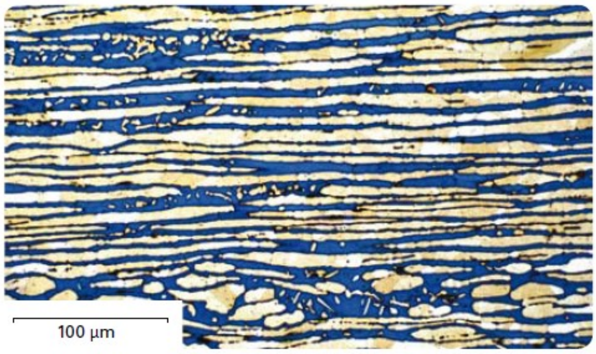


Figure 1 Typical transverse section microstructure of a duplex stainless steel Showing continuous ferritic matrix, etched dark, and austenite bands running parallel to the rolling direction of the plate. Source [19]

Combining characteristics of both ferritic and austenitic stainless steel (SS) when welded correctly.

When welded incorrectly, the tendency to form detrimental intermetallic phases significantly increases, which could lead to a catastrophic failure.

Duplex Stainless Steels typically comprise approximately equal amounts of body-centered cubic (bcc) ferrite, α-phase and face-centered cubic (fcc) austenite, γ-phase, in their microstructure. [1]

The three basic variety of DSS includes, low-alloy, intermediate alloy, and highly alloyed, or super duplex stainless steel (SDSS) grades, grouped according to their pitting resistance equivalent number (PREN) with nitrogen and are shown in Table 1. The most widely used alloys are DSS-grade 2205+ and SDSS-grade 2507[1]

25 Cr duplex such as Alloy 255 with PREN* less than 40

Super duplex (PREN 40-45), with 25-26Cr and increased Mo and N compared with 25 Cr grades, such as 2507[1]

PREN * = Pitting resistance equivalent number

$$=\%Cr + 3.3(\%Mo + 0.5\%W) + 16\%N$$

The DSSs most commonly used today in refineries include those with 22 %, 25 % and 27 % Cr. The 25 % Cr (super duplex grades) and 27 % Cr (hyper duplex grade) usually also contain more molybdenum and nitrogen, and so have higher PREN values than the 22 % Cr duplex steels.

Table 1 Chemical compositions of commonly used Duplex SS and other alloys Source [1]

Composition, Wt. % (Single Value Max.)													
UNS No.	Common Designation	C	Mn	S	P	Si	Cr	Ni	Mo	Cu	W	N	PREN
Low –alloy grades (PREN <32)													
S31500	3RE60	0.03	0.2-2.0	0.03	0.03	1.4-2.0	18.0-19.0	4.25-5.25	2.5-3.0	-	-	0.05-0.20	28
S32001	19D	0.03	4-6	0.03	0.04	1.0	19.5-21.5	1.0-3.0	0.6	1.0		0.05-0.17	23.6
S32304	2304	0.03	2.5	0.04	0.04	1.0	21.5-24.5	3.0-5.5	0.05-0.6	0.05-0.06		0.05-0.2	25
S32404	UR50	0.04	2.0	0.01	0.3	1.00	20.5-22.5	5.5-8.5	2.0-3.0	1.0-2.0	--	0.2	31
Intermediate-alloy grades (PREN 32-39)													
S31200	44LN	0.03	2.0	0.03	0.045	1.00	24.0-26.0	5.5-6.5	1.2-2.0	….	…	0.14-2.0	33
S31260	DP3	0.03	1.0	0.03	0.03	0.75	24.0-26.0	5.5-7.5	2.5-3.5	0.2-0.8	0.10-0.5	0.10-0.30	38
S31803	2205	0.03	2.0	0.02	0.03	1.00	21.0-23.0	4.5-6.5	2.5-3.5	..	..	0.08-0.20	34
S32205	2205 +	0.03	2.0	0.02	0.03	1.00	22.0-23.0	4.5-6.5	3.0-3.5	..	..	0.14-0.20	35-36
S32550	255	0.03	1.5	0.03	0.04	1.00	24.0-27.0	4.5-6.5	2.9-3.9	1.5-2.5	..	0.10-0.25	38
S32900	10RE51	0.06	1.0	0.03	0.04	0.75	23.0-28.0	2.5-5.0	1.0-2.0	..	…	…	33
S32950	7-Mo Plus	0.03	2.0	0.01	0.035	0.60	26.0-29.0	3.5-5.20	1.0-2.5	…	…	0.15-0.35	35
Superduplex grades (PREN>40)													
S32520	UR52N+	0.03	1.5	0.02	0.035	0.80	24.0-26.0	5.5-8.0	3.0-5.0	0.5-3.0	…	0.20-0.35	41
S32750	2507	0.03	1.2	0.02	0.03	1.0	24.0-	6.0-	3.0-	0.	…	0.24-	>41

					5		26.0	8.0	5.0	5		0.32	
S32760	Zeron100	0.03	1.0	0.01	0.03	1.0	24.0-26.0	6.0-8.0	3.0-4.0	0.5-1.0	0.5-1.0	0.30	>40
S32906	Safurex	0.03	0.8-1.5	0.03	0.03	0.5	28.0-30.0	5.8-7.5	1.5-2.6	0.8	…	0.30-0.4	>41
S39274	DP3W	0.03	1.0	0.02	0.03	0.8	24.0-26.0	6.0-8.0	2.5-3.5	0.2-0.8	1.5-2.5	0.24-0.32	42
S39277	AF918	0.025	….	0.002	0.025	0.8	24.0-26.0	4.5-6.5	3.0-4.0	1.2-2.20	0.8-1.2	0.23-0.33	>41

Alloy Design and Alloying additions of Duplex Stainless Steels

LDX (Lean Duplex), DX (Duplex), EN (European Standard), No (Number) UNS(Unified Numbering System for Metals and alloys)

Table 2 Standard compositions of some commonly used Duplex Stainless steels

Grade	EN No./UNS	Type	Approx. Composition					
			C	Cr	Ni	Mo	N	Mn
2101 LDX	1.4162/S32101	Lean	0.04	21.0-22.0	1.35-1.70	0.3-0.8	0.2-0.25	4-6
DX 2202	1.4062/S32202	Lean	0.03	21.5-24.0	1.0-2.8	0.45	0.18-0.26	2.0
2304	1.4362/S32304	Lean	0.03	21.5-24.5	3-5.5	0.05-0.6	0.05-0.2	2.5
2205	1.4462/S32205	Standard	0.03	22-23	4.5-6.5	3.0-3.5	0.14-0.2	2.0
2507	1.4410/S32750	Super	0.03	24-26	6-8	3-5	0.24-0.32	1.2

Table 3 Role of alloying elements Source [1]

Element	Wt %	Element Role	Alloying Characteristics
Cr	18-30%	Ferrite former	Improve corrosion resistance Ferrite content increase with increase in Cr, Higher Cr disturbs phase balance
Ni	4-8%	Austenite former	Changes Crystal Structure from ferrite to austenite Slowing down formation of intermetallic detrimental phases.
Mo	<5%	Ferrite former	Improved Pitting resistance. Increased tendency to form detrimental intermetallic phases if Mo content is too high.
N	0.14%	Austenite former	N causes austenite to form from ferrite at elevated temperatures, allowing for restoration of an accepted balance of austenite to ferrite after a rapid thermal cycle in the HAZ later welding. Additions of N increase pitting and crevice corrosion resistance and strength. Delays the formation of intermetallic phases. Offsets the formation of sigma phase in High Cr, High Mo Steels.

Welding Metallurgy of DSS

The Mechanical & Corrosion performance of the Duplex Stainless Steels weldments is depended on ferrite/austenite ratio, developed features of the microstructure which in turn depended on the phase transformations during associated weld thermal cycles during welding [18].

The iron-Chromium-nickel ternary equilibrium diagram is a roadmap to foresee the metallurgical behaviour. Fig shows a 65 % rich Iron portion of Fe-Cr-Ni ternary alloys. Alloys with composition in band 1 will undergo solidification as either fully austenitic or austenitic with small amount of residual ferrite content which becomes susceptible to Hot Cracking during welding.[18].

Alloys with compositions in bands 2, 3 and 4 will undergo solidification as ferrite; on further cooling part of the ferrite transforms to austenite at temperature below ferrite solvus. [18].

In band 2 about 20-30% of vermicular ferrite is retained at room temperature. In band 3 about 50% of the acicular ferrite can be retained. The Duplex Stainless steels composition falls in band 3. In the high Chromium equivalent band 4 almost 80-100% of the ferrite will be retained. [18].

The transformation sequence on cooling from the liquid state can be represented as follows

$L \longrightarrow L + \delta \longrightarrow \delta \longrightarrow \delta + \gamma$

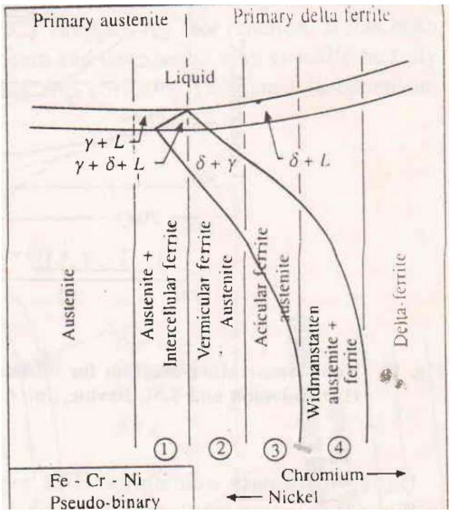


Figure 2 Schematic constant iron section at 65% iron of the Fe-Cr-Ni ternary diagram

The transformation sequence of Duplex SS is as under:-

$L \longrightarrow L + \delta \longrightarrow \delta \longrightarrow \delta + \gamma$

The duplex stainless steels are preferably welded after solution treatment in the range 1000- 1100º C the temperature and time being decided by steel composition and section size, respectively. This heat treatment would result in nearly equal proportions of austenite and ferrite in a typical DSS.[18].

During welding in the heat affected zone (HAZ) austenite is transformed to ferrite on heating whenever the ferrite solves temperature is exceeded. On consequences is the austenite dissolution is the growth of ferrite grains. [18].

Coarse grain regions are commonly observed adjacent to the fusion line. Which is a similar type of phenomena occurs in ferritic stainless steels. [18].

An isothermal precipitation diagram for 2304, 2205, and 2507 duplex stainless steels is shown in Figure 2(Ref. 4, 5, 6, 7). The start of chromium carbide and nitride precipitation begins at the relatively "slow" time of 1–2 minutes at temperature.[1]

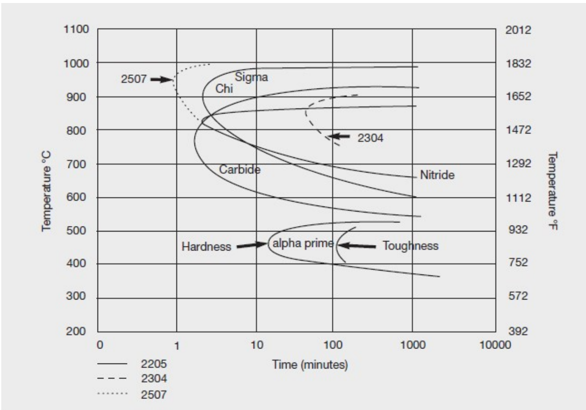


Figure 3 isothermal precipitation diagram for 2205 duplex stainless steel, annealed at 1050 ºC (duplex grades 2307 and 2507 are shown for comparison)

The application of DSS is generally limited to the temperature range -20 to +300° C due to precipitations of the detrimental phases above 300 °C.

Scope of the Work (Literature survey work done so far & research gap Identification)

It is well documented through various research that optimum corrosion resistance and mechanical properties throughout a DSS weldment are achieved when the phase balance of ferrite to austenite is 50:50. However, achieving a 50:50 phasebalance of ferrite to austenite ($\alpha \rightarrow \gamma$) in a weldment practically has proven to be difficult due to many variables involves such as composition of the base metals, filler metal, welding processes, and thermal history of the steel. [1]

Various research outcome on Welding of Duplex stainless steels have suggested that optimal corrosion resistance and set of mechanical properties are achieved when 35 to 60% ferrite content is maintained throughout the weldment. [1]

W. A. Baeslack et al (1978)Technical Note onhis research on Austenitic SS weldments prepared by GMAW-Pulse process weldment with Type 310 or

312 filler metal on a Type 304L base metal varying Ferrite Number (FN) investigated preferential dissolution of the ferrite or austenite-ferrite interphaseregions also explained the relationship of continuous ferrite network with susceptible to Stress corrosion cracking. [2]

D. J. Kotecki (1986) experimented on alloy 2205 and 225 in as welded conditions, using self-shielded flux core arc welding electrodes of 8.5% and 10 % Nickel, he found that weld deposit below 60 EFN for alloy 2205 and 255 provides sufficient ductilityand toughness that a side bend test, Charpy V-notch energy of better than 20 ft-lb (14.7) at-50°F (-46°C) . Ferrite content above 30 EFN result in yield strength and tensile strength in the weld metal matching to base metal strength. Addition of 4% Moly deliberatelyadded to Alloy 255 for improving corrosion resistance, adversely shown possibility of embrittlement.[3]

J. C. Lippold,I. Varol And W. A. Baeslack Iiet al (1989) evaluated solidification cracking tendencies of two different alloys SAF 2205 &Ferralium 255. According to their research work, SAF 2205 shows weld solidification cracking susceptibility somewhat less than that duplex alloy Ferralium 255. While comparing with Austenitic Stainless steels, Cracking in the duplexalloys was found to be intermediate between Type 304/FN 8 (ferrite solidification)and Type 304/FN 0 (austenite solidification) . Thereby there is a big role of ferrite & primary mode of solidification in Solidification cracking tendencies[4]

S.A. Ta´vara a, M.D. Chapetti et al (2001) work on Influence of nickel on the susceptibility to corrosion fatigue of duplex stainless steel welds.
They have tries Ni 2.8, 4.7, 6.8 and 9.8 wt% and measured by
three point bending fatigue tests in air & normalised environments accompanied by with anodic polarisation. Research outcome was Electrode with 4.7% Ni provided very satisfactory Corrosion Fatigue properties.[5]

S.K. Seshadri b, S. Sundaresan et al (2003) work on effect of weld metal chemistry & H.I on structure and properties on DSS Welded joints showed that Nickel is very effective in controlling the ferrite /austenite ratio than the cooling rate. Differences in ferrite /austenite ratio has little effect on
Hardness but the toughness is highly depended on ferrite content in addition to other factors such as residual stresses, precipitation morphology.

They practically showed possibility of EBW Welding Technique for joining DSS provided with care of Nickle enrichment to control effect of cooling rate by high energy density processes. [6]

P. Bala Srinivasan et al (2006) studied the impact strength & corrosion behaviour of SMAW Welded dissimilar weldments betweenUNS 31803 and IS 2062 steels.Results have shown thatgeneral corrosion resistance of the weld metalwith E309 is superior whilst the welds with E2209electrodes exhibit better passivation behaviour.[7]
Welds produced with E309 electrodes have the highest
Susceptibility to pitting in chloride solution. But E2209 electrodes for joining DSS and CS is most suitable for achieving bettermechanical and corrosion properties.[7]

J.M. Pardal et al (2007) reported effect of multi pass (GTAW Root pass& SMAW fill & cap pass) welded SDSS 32750 on toughness -Mechanical &Pitting Corrosion Behaviour as Low Nickel filler metal employed in root pass result in low austenite formation & deleterious phases while SMAW Fill & Cap Pass resulted in low toughness. [8]

R.K. Singh Raman et al (2010) Investigated on Super duplex 2507 grade, effect of Nitrite additions in Mgcl2 SSRT Solution. They have researched out that upto 2800 ppm additions susceptibility of Ch-SCC is suppressed but beyond 5600 ppm Nitrile additions, susceptibility of Ch-SCC rate increases. [9]

D.J.Kotecki (2010) in his publications [ ] provided Recommendations for use of DSS 2205 with at least 0.14% N added, proper H.I & Interpass Temperature for obtaining desired microstructure & Mechanical & corrosion performance.[10]

A.I. Aljoboury et al (2010), conducted SCC Test in Brine Solution & Electrochemical Analysis Pitting measurement UNS S31603 andUNS S32750 wrought samples and provided recommendations for building brine recirculation pumps.UNS S32750 samples shown superior stress corrosion resistance than UNS31603 material in the same testing conditions.[11]

A review paper on “Welding of Duplex SS” by Jatandeep Singh et al (2013) explained the importance of balancing ferrite to austenite, way of avoiding &

minimizing formation of deleterious intermetallic and non-metallic phases, deleterious effect of hydrogen on duplex stainless steel and measuring technique of ferrite contents in Duplex SS Weldments.[12]

Zhiqiang Zhang et al (2013) In their research work, investigated the relationship between microstructure developed by Flux-cored arc welded metal for corrosion behaviour using Electrochemical potentiokinetic reactivation technique to study selective corrosion and concluded selective corrosion of secondary austenite over primary austenite & ferrite. Apart from this Localised corrosion possibility around Cr2N and sigma phase in HAZ. [13]

Johan Pilhagen (2014) et al, investigated on Lean LDX material that the fracture toughness at sub-zero temperatures increases with increasing nickel content in therange from 1to9 wt% nickel.[14]

Jingqiang Yang et al,(2014) conducted weld failure analysis of 2205 duplex stainless steel nozzle with a root cause that Localized unevendistribution of ferrite/austenite with 80-90% ferrite in weld responsible for the cleavage fracture by crack propagation mechanism along columnar grains. [15]
J.H. Potgieter et al (2008) in his research work on Influence of nickel additions (5%, 7%, 9%and 13%) on the pitting corrosion behaviour of low nitrogen 22%Cr series duplex stainless steels. Research showed that Uniform corrosion behaviour of the alloys predominantly controlled by phase composition and ratio while pitting resistance is controlled by nickel contents.[16]

J.C. deLacerda et al, (2015) Corrosion behaviour of UNSS31803 steel with changes in the volume Fraction of ferrite and the presence of chromiumnitride. Under this investigations, Microstructural variations in the plates were produced by thermal annealingtreatments at1200 °C and1300 °C. Steel annealed at1060 °C showed greater resistance to stress corrosion cracking than steel annealed at 1300 °C. Steel annealed at 1300 °C had the lowest critical pitting temperature.

Zhiqiang Zhang at al (2016), Use of N2 as shielding gas promote solid solution in the austenite. Pitting corrosion resistance preferentially attack on Secondary austenite than Primary austenite due to less amount of Cr and Mo available in the phase. Presence of inclusion due to use of E2209T1 flux based process result in poor pitting corrosion resistance.[17]

Findings of the literature survey mention that there has been a lack of data to support a minimum ferrite content requirement for DSS weld metal to provide resistance to chloride stress corrosion cracking (CSCC). Various organizations require 30 to 60%, 30 to 70 Ferrite Number, 35 to 75%, etc.

There are two concerns about the minimum ferrite content requirement: 1. maintaining required minimum yield strength and 2. Providing resistance to chloride SCC.

Dr. D.J.Kotecki in his work [3]reported on yield strength issue and found that yield strength was maintained down to as low as 30 FN (about 21% ferrite), and no ferrite lower limit was identified. & no further investigation is made into SCC resistance.

Among Industrial clients, there has been dispute over this issue of required minimum ferrite Content. The issue doesn't involve GTAW or GMAW because the low oxygen content (typically less than 150 ppm) of the weld metal provides high toughness at relatively high ferrite content, so filler metal manufacturers can aim for about 50% ferrite in their filler metal without concern about toughness. But for flux shielded filler metals (SMAW, FCAW, SAW), the higher oxygen content (typically 600 ppm or more) reduces toughness, so the filler metal manufacturer aims for weld metal deposits at the low end of specified ferrite ranges in order to meet toughness requirements at 40°C. There is, of course, a degree of variation in weld metal ferrite content and in reproducibility of measurement.

So it happens fairly often that a fabricator measures a little less than the specified ferrite requirement, or the fabricator measures above the specified limit but his customer measures ferrite content for the same lot of filler metal and obtains a value below the specified limit. As a result there is a battle over whether or not the filler metal is acceptable and a delay in the project results while the parties to the dispute try to resolve it. This wastes a lot of time and money.

Metallurgical point of view, DSS requires solidification as 100% ferrite and formation of austenite only in the solid state. This mode is responsible for both high yield strength and resistance to chloride SCC. The WRC1992 Diagram indicates 100% ferrite solidification at as low as 20Ferrite Number (about 14% ferrite).

Experimental Work (Summary)

Present work has been carried out by collaborating with a reputed filler metal manufacturer to investigate required minimum ferrite content to obtain required minimum yield strength and resistance to chloride stress corrosion cracking. Under this project, the filler metal producer provided electrodes aimed at the low end of normal DSS ferrite specifications, and below, and we have examined the SCC resistance and the yield strength of the welded joint.

To vary (reduce) the ferrite content, We asked to prepare SMAW electrodes with increase the Ni content starting from the standard Ni level in the 2209 electrode design. Three Different Nickel targets were tried out 9-10 % Ni, 10-11% Ni & 11-12% Ni, Increasing the Ni content, leaving all other elements as in the standard composition, has the benefit of leaving the pitting resistance index (PREN) unchanged while the ferrite content is reduced. By far, 2209 is the most common of the duplex stainless steel electrodes.

Methods adopted

1. Preparation of Weld Test Coupons of 300 mm X 150 mm X 25 mm (As Per ASME SEC IX BPVC Code Rev. 2015) using SMAW Electrodes of different three Ni Targets (09-10%, 10-11% & 11-12%) with Weld Parameters as mentioned below:-

   Process Parameters

a. Voltage : 20 V (recommended Range of 18-22 V)
b. Current: 110 A (80-120 A)
c. H.I : 1.5-2.5 KJ/mm
d. Intepass Temperature: below 150 °C
e. Travelling Speed: 150-180 mm/min
   Backing of Electrodes: 250 °C for 2 hrs.
f. Preheating temperature of plates: None
g. PWHT. Not required.
h. Weld Position : Flat
i. WEP : 60 Degree groove.
j. Bead deposition: Stringer bead technique

2 .Theoretical calculation of FN using WRC-1992 Diagram & Practical Validation through

2a. ASTM E-563 Image Analysis of weld Micro.

2b. Fischer Feritscope® instrument

2c. Chemical analysis of WM

2d. Prediction of Ferrite Number from the given composition of BM & Filler Metal using WRC-1992 diagram.

3. Radiography Test
4. Testing tensile properties by a round all weld metal tensile specimen as found in AWS A5.4 specification for stainless steel covered electrodes as per AWS B4.0
5. Transverse Tensile Tests as Per ASME SEC IX BPVC 2015 Code.
6. Hardness Survey BM, HAZ, WM AS PER E-384, EN ISO 9015-1:2011
7. Microardness profile survey BM, HAZ As Per E-385 at 500gmf.
8. Impact Test at -46° C, value reported in Joule.
9. Bend Test as Per ASME SEC IX BPVC 2015 Code
10. Macro examination ASTM-E-381-01
11. SCC Test in NaCl Environment As per ASTM G123
12. Pitting Corrosion Test as per ASTM G48 Method A

The aim is to establish required minimum ferrite content for meeting specified minimum yield strength and SCC resistance with the 2209 alloy.

Test Results summary & Discussions

-Theoretically (WRC-1992 Diagram) & Physically (Fischer Ferritoscope & Volume fraction methods) Confirmations of FN below 40 and below with experimental electrodes employed in increase order in Nickel Content from standard commercial E2209 -16 9% Nikel design (Low Nickel 9.5-10.5 wt%, Medium Nickel 10.5-11.5 wt% and High Nickel 11.5-12.5%wt

-The ASTM A240 standard for 2205 base metal requires 450 MPa yield strength minimum, and 655 MPa tensile strength minimum,all-weld metal test results comfortably exceed those requirements.

- ISO 3581 requires yield strength for the 22 9 3 N L or 2209 filler metal to be 450 MPa minimum. So all those requirements are exceeded.

Note * As AWS A5.4 only requires tensile strength, not yield strength.

Hardness Values 3 points in BM, WM & HAZ is average 240 VPN acceptable ranges.

Micro hardness varations along FZ, HAZ and BM acceptable limit 250 VPN.

Impact Test at -46 °C test temperature results exceed 27 Joule, Min CVN Requirement as per ASME SEC IV Code.

Table 4 Comparative Stress Corrosion cracking resistance in accelerated laboratory tests.

Test Coupon ID	ASTM G36 45% MgCL 155 °C (b.p) U-bend 500 hrs Test	ASTM G 123 25% NaCl, pH 1.5 106°C (b.p.) U-bend 1000 Hrs.	25% NaCl 106°C (b.p.) U-bend	NACE TM 0177-2005 Method "A".(5% NaCl+0.5% Gl.Acetic in distilled water) 720 Hrs
E2209(10Ni22Cr)	Expected*	Not anticipated	Not anticipated	Not anticipated
E2209(11Ni22Cr)	Expected*	Not anticipated	Not anticipated	Not anticipated
E2209(12Ni22Cr)	Expected*	Not anticipated	anticipated	anticipated

- SANDVIK / AVESTa Steels / Allegheny etc.. Data Sheet indicates 2205 is not resistant to SCC in boiling magnesium chloride (ASTM G36 test)so the ASTM G36 test method is not tried out.

ASTM G 123 Test Specimen under test for 1000 Hrs in 25 % NaCl, boiling acidified solutions in restraint conditions for all weld test coupons. Results is awaited, No SCC is expected as per DataSheet for Standard 2209 Alloy Data Sheet.

ASTM G48 Practice An exposure 24 Hrs. of all weld test coupons in 6 % FeCl3 test solutions at 22 °C did not show pitting corrosion on any of the sample under test.

Prediction of Weld Metal ferrite Content using WRC-1992 diagram

Case 1. Considering dilution from Base Metal 20% & 60% from FM

	Base Metal 2	Base Metal 1	Filler Metal	Weld Metal	Synthetic Base Metal
C, %	0.03	0.03	0.017	0.022	0.030
Mn, %	1.50	1.50	1.11	1.266	1.500
Cr, %	22	22	22.33	22.198	22.000
Ni, %	5.5	5.5	12.75	9.850	5.500
Mo, %	3.3	3.3	3.2	3.240	3.300
Nb, %	0	0	0	0.000	0.000
Cu, %	0	0	0	0.000	0.000
N, %	0.17	0.17	0.18	0.176	0.170
% of Joint	20	20	60	100	
Creq	25.3	25.3	25.53	25.438	25.3
Nieq	9.95	9.95	16.945	14.147	9.95
FN	85.3	85.3	13.0	25.8	

Figure 4 COMPOSITION OF BM & FM

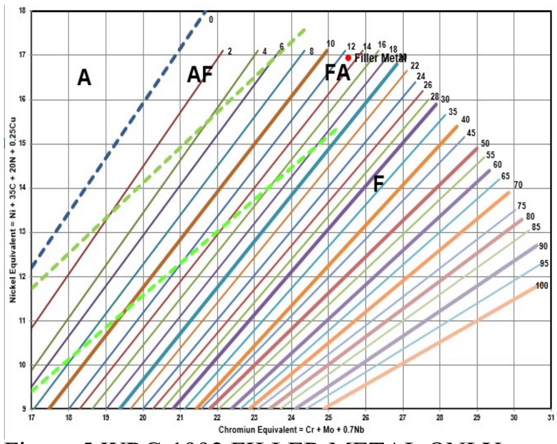


Figure 5 WRC-1992 FILLER METAL ONLY

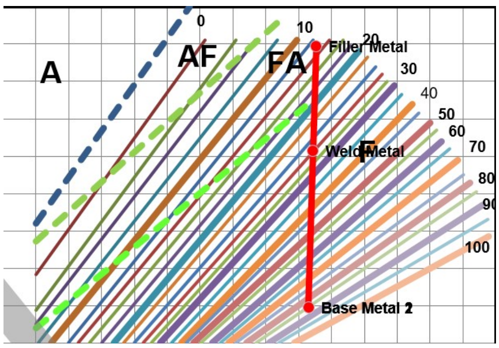


Figure 6 Enlarged view indicating Aprx. FN 26

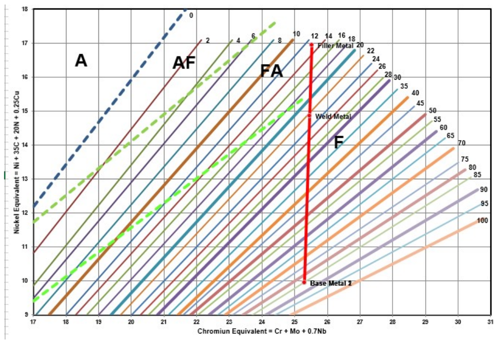


Figure 7 WRC 1992 Diagram Predicting FN of WM

Case 2. Considering dilution from BM 15% & 70% from FM

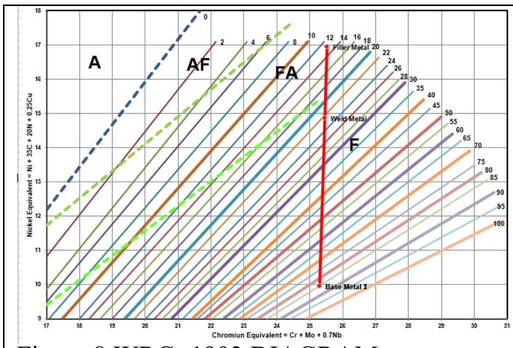


Figure 8 WRC -1992 DIAGRAM PREDICTING FN 22

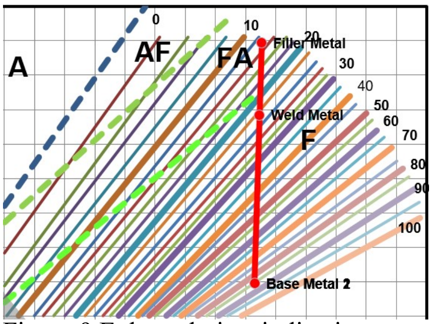


Figure 9 Enlarged view indicating approx. FN 22

Measurement of Weld metal ferrite content using Fischer make feritscope® calibrated instrument (as per ISO: 8249)

Coupon lD - E22O9(l,2Ni22Crl, Welding Process - SMAW, Filler Wire - E22O9-LG (GRTNOX-2209), Welding Position – Flat

Instrument utilized was Fischer Ferritscope Germany Make: Fischer 2531

Figure 10 Calibrated Fischer Ferritscope Germany Make: Fischer 2531

Sr. No	Description	Ferrite Number	Average
1	Weld	22.5, 23, 21.9, 22.0,21.9	22.5

Measurement of Weld metal ferrite content using ASTM E-562 Volume fraction measurement using systematic point count method.

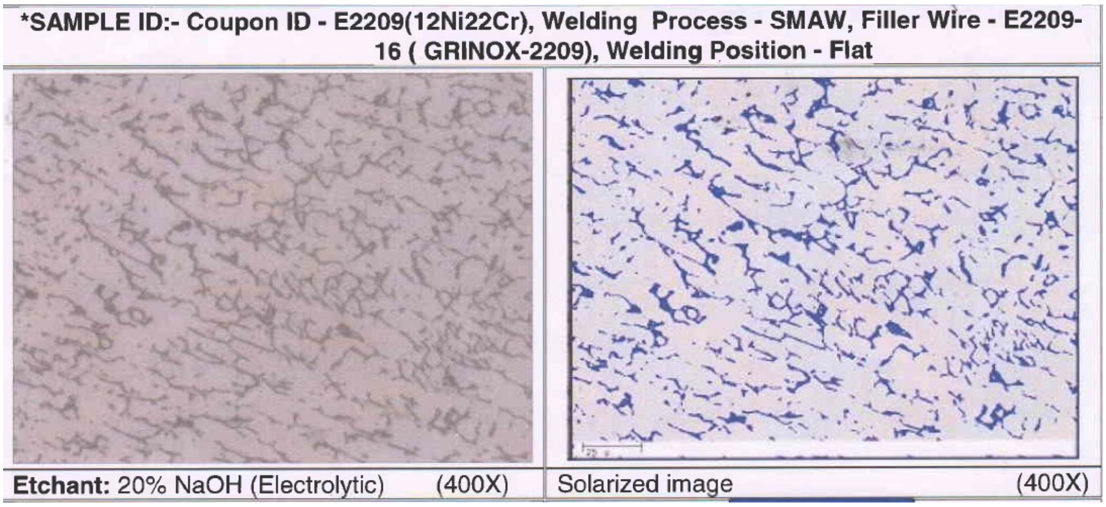


Figure 11 PHASE QUANTIFICATION BY IMAGE ANALYSIS TECHNIQUES

Specification of Electrodes E 2209-16 (GRINOX-2209) , (12Ni 22Cr)
Electrode Specifications
AWS/SFA 5.4: E2209-16, IS 5206 : E 22 15 3 LR 26
ASTM A 182 gr. F51UNS S31803DIN 1.4462
SMAW Electrode GRINOX 2209 E 2209-16 size 3.15 X 350 mm

Experimental electrode design for research study work
Low Nickel (9.5-10.5%wt Ni), Medium Nickel (10.5-11.5%wt Ni) High Nickel(11.5-12.5%wt Ni) . rest composition is same as per Std E2209-16 alloy design

Figure 12 SMAW ELECTRODE

Preparation of All weld Test Set up according to AWS B 4.0

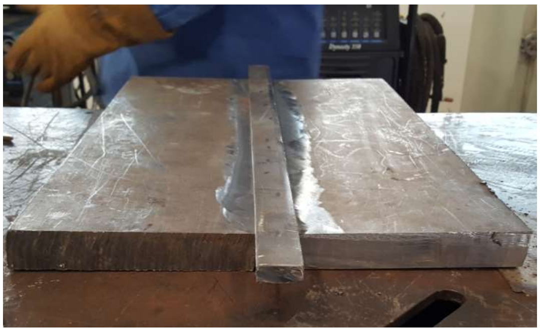


Figure 13 Backing Strip Weld

Figure 14 C-Clap Restraint (Front view)

Figure 15 (Side View)

Figure 16 Wire Brush finished Test Piece

Figure 17 Fill Pass completed

Figure 18 Root pass completed

Figure 19 Use of digital thermometer to control less than 150 °C inter pass temperature.

Figure 20 Use of templistic to control less than 150 °C inter pass temperature.

Figure 21 Welding by AWS qualified experienced welder

Process Parameters
Voltage : 20 V (recommended Range of 18-22 V)
Current: 110 A (80-120 A)
H.I : 0.5-2.5 KJ/mm
Intepass Temperature: below 150 °C
Travelling Speed: 150-180 mm/min (Average T.S 172 mm/min)
Backing of Electrodes: 250 °C for 2 hrs.
Preheating temperature of plates: None
PWHT. Not required.
Weld Position : Flat
WEP : 60 Degree groove.
Bead deposition: Stringer bead technique

Mechanical Test

Transverse Tensile Test As per ASME SEC IX Ed 2015

Coupon lD - E2209(12Ni22Cr, Welding Process - SMAW, Filler Wire - E22O9-15 (GRINOX-2209), Welding Position – Flat

Sample Mark	Sample 1	Sample 2	Min required
Thickness (mm)	25.15	*22.90*	*Y.S. =450 Mpa* *T.S = 650 Mpa*
Width (mm)	19.29	19.13	
Area (mm2)	485.14	438.08	
Ultimate Load (N)	370590	340620	
UTS (N/mm2)	764	778	
Fracture	AT P.M.	AT P.M.	
Fracture Type	Ductile	Ductile	

Figure 22 Transverse Tensile Specimen before fracture

Figure 23 Transverse Tensile Specimen After fracture

Figure 24 Specimen under Tensile load Press capacity 60 Ton Capacity

Figure 25 Fractured specimen shows fracture from the P.M.

All weld Tensile Test method as per AWS B4.0

Figure 26 Prepared specimen for All weld Test

Figure 27 Initial gauge length measurement ~ 50 mm

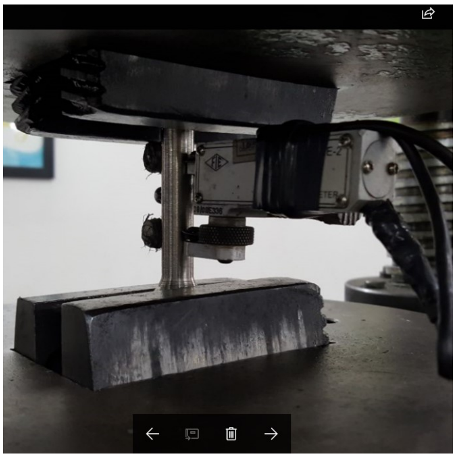


Figure 28 Specimen under Tensile load of UTM Machine with 40 Ton capacity

Fracture within Gauge length at 91740 N

Figure 29 Final Diameter 7.32 mm measurement.

Figure 30 Final Length Measurement : 64.87 mm

Welded COoupon Macro Hardness As PER E-384, EN ISO 9015-1:2011
Instrument Utilized : Vickers cum Brinnel Hardness tester

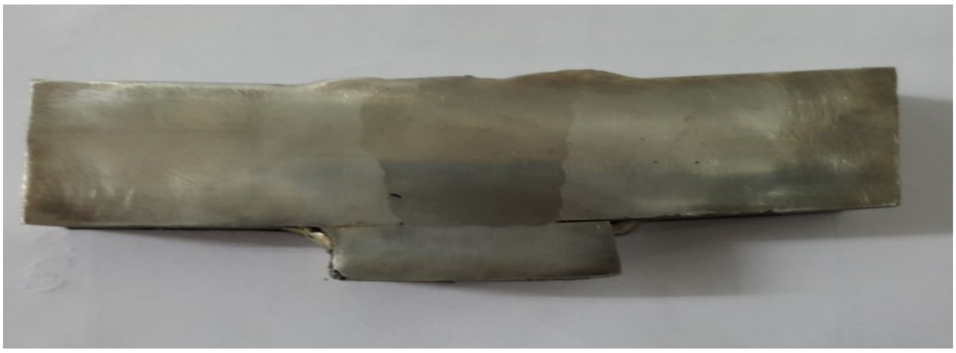


Figure 31 Welded Coupon for Hardness Measurement

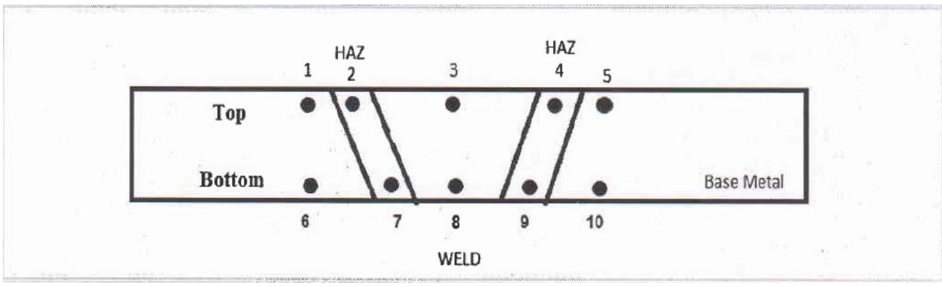
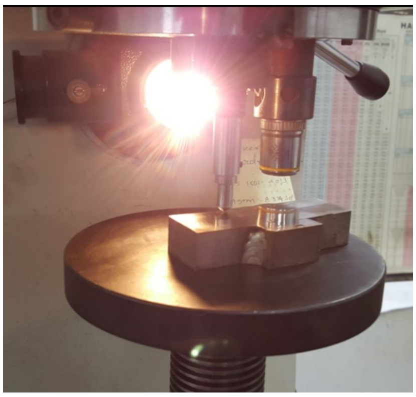


 **Figure 32 Brinnel cum Rockwell hardness tester**	 **Figure 33 Specimen being measured for hardness at different 10 locations with 10 Kgf applied Minor load & 50 Kgf Major load according to AS PER E-384, EN ISO 9015-1:2011**

Conclusion

- Nickel being Austenite Stabilizer, increases the Volume fraction of the Austenite in Weld metal, Hence the Cr eq / Ni eq ratio lowers down to 2.3. Which in turn reduces the ferrite Number(FN)

-The effect of FN between 20-40, less than the FN Specifications for Duplex SS (35 to 60 FN), examined for optimum Yield strength property & resistance to stress corrosion test.
-Less Specification on FN between 20 to 40 FN matching the base metal strength properties.
-There may be possibility of Secondary austenite phase presence at the interface of Ferrite & Primary austenitic phase boundary due to multiple weld passes. However , To be confirmed with high resolution microscopy.
- Transverese tensile test results shows that breaks happens from Base Metal hence Weld metal is stronger than base metal.
-Radio graph showing no defects like slag inclusion or presence of Intermettalic precipitations.
-Absence of Intermetallic precepitations were confirmed through ASTM A 923 Method.
-Theoretically (WRC-1992 Diagram) & Physically (Fischer Ferritoscope & Volume fraction methods) Confirmations of FN between 20 To 40

-The ASTM A240 standard for 2205 base metal requires 450 MPa yield strength minimum, and 655 MPa tensile strength minimum, all-weld metal test results comfortably exceed those requirements.

- ISO 3581 requires yield strength for the 22 9 3 N L or 2209 filler metal to be 450 MPa minimum. So all those requirements are exceeded.

Note * As AWS A5.4 only requires tensile strength, not yield strength.

Micro and Macro Hardness Values 3 points in BM, WM & HAZ is average 240 acceptable range.

References:-

[1] B. Messer, V. Oprea, and A. Wright, “Duplex stainless steel welding : best practices *,” 2007.

[2] B. Y. W. A. Baeslack, D. Duquette, and A. N. D. W. F. Savage, “Technical Note : Stress Corrosion Cracking in Duplex Stainless Steel Weldments,” pp. 175–177.

[3] D. Kotecki, “Ferrite control in duplex stainless steel weld metal,” *Weld. J.*, 1986.

[4] I. Varol, W. A. Baeslack, and J. C. Lippold, “Characterization of weld solidification cracking in a duplex stainless steel,” *Metallography*, vol. 23, no. 1, pp. 1–19, 1989.

[5] S. A. Távara, M. D. Chapetti, J. L. Otegui, and C. Manfredi, “Influence of nickel on the susceptibility to corrosion fatigue of duplex stainless steel welds,” *Int. J. Fatigue*, vol. 23, no. 7, pp. 619–626, 2001.

[6] V. Muthupandi, P. Bala Srinivasan, S. K. Seshadri, and S. Sundaresan, “Effect of weld metal chemistry and heat input on the structure and properties of duplex stainless steel welds,” *Mater. Sci. Eng. A*, vol. 358, no. 1–2, pp. 9–16, 2003.

[7] P. B. Srinivasan, V. Muthupandi, W. Dietzel, and V. Sivan, “An assessment of impact strength and corrosion behaviour of shielded metal arc welded dissimilar weldments between UNS 31803 and IS 2062 steels,” *Mater. Des.*, vol. 27, no. 3, pp. 182–191, 2006.

[8] S. S. M. Tavares, J. M. Pardal, L. D. Lima, I. N. Bastos, A. M. Nascimento, and J. A. de Souza, “Characterization of microstructure, chemical composition, corrosion resistance and toughness of a multipass weld joint of superduplex stainless steel UNS S32750,” *Mater. Charact.*, vol. 58, no. 7, pp. 610–616, 2007.

[9] R. K. S. Raman and W. H. Siew, “Role of nitrite addition in chloride stress corrosion cracking of a super duplex stainless steel,” *Corros. Sci.*, vol. 52, no. 1, pp. 113–117, 2010.

[10] D. J. Kotecki, “Some pitfalls in welding duplex,” pp. 0–4.

[11] A. I. Aljoboury, A. H. I. Mourad, A. Alawar, M. Abou Zour, and O. A. Abuzeid, “Stress corrosion cracking of stainless steels recommended for building brine recirculation pumps,” *Eng. Fail. Anal.*, vol. 17, no. 6, pp. 1337–1344, 2010.

[12] J. Singh, N. Goswami, A. Engineering, and N. Delhi, “Welding of Duplex Stainless Steel,” vol. 1, no. 4, 2013.

[13] Z. Zhang, H. Jing, L. Xu, Y. Han, and L. Zhao, “The influence of microstructural evolution on selective corrosion in duplex stainless steel flux-cored arc welded joints,” *Corros. Sci.*, 2016.

[14] J. Pilhagen and R. Sandström, “Influence of nickel on the toughness of

lean duplex stainless steel welds," *Mater. Sci. Eng. A*, vol. 602, pp. 49–57, 2014.

[15] J. Yang, Q. Wang, Z. Wei, and K. Guan, "Weld failure analysis of 2205 duplex stainless steel nozzle," *Case Stud. Eng. Fail. Anal.*, vol. 2, no. 2, pp. 69–75, 2014.

[16] J. H. Potgieter, P. A. Olubambi, L. Cornish, C. N. Machio, and E. S. M. Sherif, "Influence of nickel additions on the corrosion behaviour of low nitrogen 22% Cr series duplex stainless steels," *Corros. Sci.*, vol. 50, no. 9, pp. 2572–2579, 2008.

[17] Z. Zhang, H. Jing, L. Xu, Y. Han, L. Zhao, and J. Zhang, "Influence of microstructure and elemental partitioning on pitting corrosion resistance of duplex stainless steel welding joints," *Appl. Surf. Sci.*, 2016.

[18] S Sunderesan, "Welding of ferritic, Martensitic and Duplex Stainless Steels", Welding Technology for Engineers, Narosa Publishing House, Page no 58-62.

[19] Corrosion testing of Stainless steels-outokompu acom, 1-2010

Bibliography

[1] John C Lippod & Damian J.Kotcki, Welding Metallurgy & Weldability of Stainless Steels,A John Wiley & Sons, Wiley-Interscience Publication 2005
[2] Basic understanding of weld corrosion- ASM metals handbook.
[3] Practical guidelines for fabrication of Duplex stainless steel, Second edition, 2009 IMDA, London UK. pp 6-21.
[4] A corrosion management & application engineering magazine from OUTOCOMPU special issue (1-2010)
[5] Acom (2-2007) Stress corrosion properties of UNS S32101 Duplex stinless steel with low nickel content
[6] AWS Metals Handbook, Vol. 1, 2 & 4.
[7] Robert Baboian, Corrosion tests and Standards: Application and Interretations-Second Edition ASTM International
[8] AWS B4.0:2007 An American National Standard Methods for Mechanical Testing of Welds7th Edition
[9] Duplex stainless steel microstructure -Robert N Gunn