Dilution Control in SMAW & GTAW Welds Involving Low Alloy Steel, Ferritic Stainless Steels & Nickel Based Alloys

Chintan R. Shah[1], Mr. Ankur Mande[2] and Dr. B.R.Rehani[3]

[1] Post Graduate Student, Department of Metallurgical and Materials Engineering, Faculty of Technology and Engineering, The M.S. University of Baroda, Vadodara.

[2] Manager, L & T – HED, Hazira, Surat.

[3] Associate Professor, Department of Metallurgical and Materials Engineering, Faculty of Technology and Engineering, The M.S. University of Baroda, Vadodara.

DOI : 10.22486/iwj/2019/v52/i1/178189

ABSTRACT

Fusion welds of overlay were prepared between ferritic stainless steel of 410s with base metal of low alloy steel of SA 387 Gr. 11 Class 2 using Ni based consumables (Inconel 182 & 82) with GTAW & SMAW processes for clad restoration. For clad restoration, most of the process licensors indicate requirement of 3 mm undiluted clean chemistry throughout thickness as per ASME Sec. II, Part C to ensure sufficient corrosion resistant during operation of a coke drum. Experiments were carried out by varying different parameters that directly affect the dilution like chemical composition of filler wire, effect of bead height, overlap and layer by layer grinding for Inconel 182 electrode. For Inconel 82 filler wire, effect of wire feed rate and melting power on dilution control were studied. The dilution level of each weld fusion was determined through geometric measurements as well as through measuring chemical composition using optical emission spectrometer of the weld cross-sectional areas. Result states that reduction in electrode diameter plays a major role in reduction of dilution. Also, with increase in overlap, the weld metal chemistry tends to move towards filler metal chemistry. For GTAW process, filler metal feed rate & melting power individually do not contribute in reducing the effect of dilution however optimizing their combination yield required results. Also, effect of variation % Fe in weld overlay on corrosion resistance was examined using ASTM G 28 method A & for cyclic polarization with NaCl environment where rate of corrosion reduces drastically with reduction in dilution.

Keywords: Clad restoration; dilution control; undiluted clean chemistry; rate of corrosion.

1.0 INTRODUCTION

The rapid exploitation of technologies in petrochemical field that require use of high temperature and pressure has led to the development of materials which can suit the requirement of such severe working conditions. Equipment like coke drums used in refineries and petrochemical plants are usually operated in corrosive environments and therefore, inside surface of this equipment must have corrosion resistant material. So, they are fabricated from clad plates which are to be joined with clad restoration process.

Many applications like clad restoration exist in which alloys of differing compositions are by fusion welding. In these applications, the final fusion zone can potentially exhibit a composition that lies anywhere between that of each alloy. The final composition and corresponding microstructure and properties of the fusion zone will be determined by the dilution level. The dilution level is, in turn, strongly affected by the welding parameters. Thus, many dissimilar metal welding applications require careful control over the welding parameters and corresponding dilution level in order to produce welds with the proper microstructure and properties for the intended service.

It is important to ensure that any weld joint surface that is exposed to corrosive media is at least as corrosion resistant as the cladding. To ensure this, most of the process licensors indicate requirement of 3 mm undiluted clean chemistry as per ASME Sec. II, part C throughout thickness.

1.1 Dilution

Dilution is defined as the change in base composition of the weld metal caused by the mixing of the base metal or the previously deposited weld metal **(Fig. 1)**. The proportion of base metal in a weld bead is characterized by the dilution ratio [1].

$$\text{Dilution Ratio (D)} = \frac{\text{Surface B}}{\text{Surface (A+B)}} \quad (1)$$

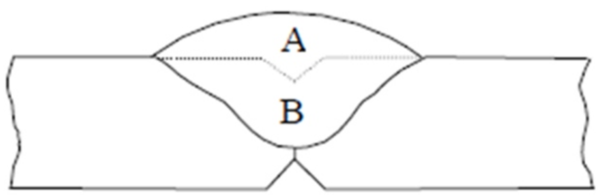


Fig. 1 : Schematic illustration of dilution showing the amount of base metal melted (B) and filler metal added (A) in a typical fusion weld [1].

The final fusion zone composition will depend on the individual compositions of the base and filler metals and the degree of dilution of the filler metal by the base metal(s). Under lying assumption for Eq. 1 is that losses by evaporation are negligible.

The other method for calculation of dilution is based on chemistry (depends on percentage of element considered.) Eq. 1 is related to area calculation while Eq. 2 given below is related to elemental analysis [2].

$$D = \frac{C_{fz} - C_{fm}}{C_s - C_{fm}} \quad (2)$$

Where, C_{fz}, C_{fm}, and Cs are the elemental compositions of the fusion zone, filler metal, and substrate, respectively, and D is the dilution level. The values for the major constituents of Fe and Ni were used and averaged to get the final dilution level of the weld.

It should be noted that each time a welding material undergoes cooling transformation phases, the analysis of the metal added by the welding product which makes it possible to obtain the same mechanical properties is different from that of the base metal, because the cooling conditions during the manufacture of the latter are very different from those which are associated with welding. Thus, by dilution effect, the molten metal has an intermediate analysis between that of the added metal and that of the base metal and this analysis can vary from one pass to another in multipass welding. This is why the majority of the operating mode procedures require a check on the properties at various levels in the welded joint and, in particular, in the root zones where the dilution ratio is the highest and consequently where the lowest impact strength values will often be found [1].

Dilution depends on various variables like voltage, current, welding speed, heat input, polarity, electrode diameter, stick out, bead separation & overlapping, preheat, interpass temperature, shielding gas composition, joint design etc.

Dilution increases with increasing heat input when the increase in heat input is achievedthrough an increase in welding current at constant welding speed. However, dilution tends todecrease with increasing heat input when increase in heat input is achieved through a reductionin speed at constant welding current.

As stick out increases, dilution decreases due to increase in beadheight. Increase in overlap also decreases the dilution due to increase in bead thickness. Anincrease in preheat or interpass temperature may increase the dilution because it reduces theamount of energy required for melting the base metal, thus increasing the base metal meltingrate. Groove joint gives less dilution compare to butt joints.

1.2 Effect of Current and Welding Speed on Dilution

Photo macrograph of typical transverse weld sections of single weld beads obtained by varying the welding current are shown in below **Fig. 2**.

The variations of weld bead size with increase in welding current are shown in below **Fig. 3**. The width of the weld-bead increases almost linearly with the welding current for constant values of the other welding parameters. The depth of penetration also shows an increase, whilst the weld height slightly decreases with increasing welding current. The rate of increase in bead width is significantly greater than the rate of increase or decrease in the penetration depth or the weld height.

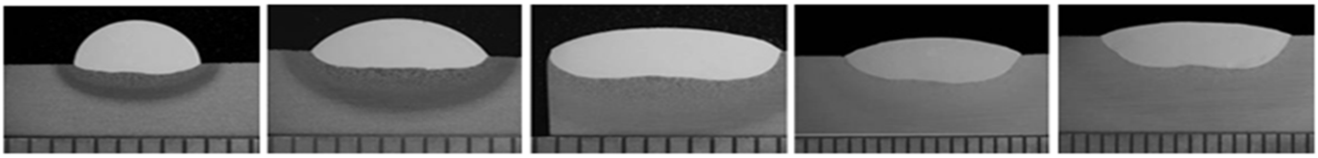


Fig. 2 : Photo macrographs of typical transverse sections of single weld bead produced by increasing current. Note the different magnifications in photographs [3].

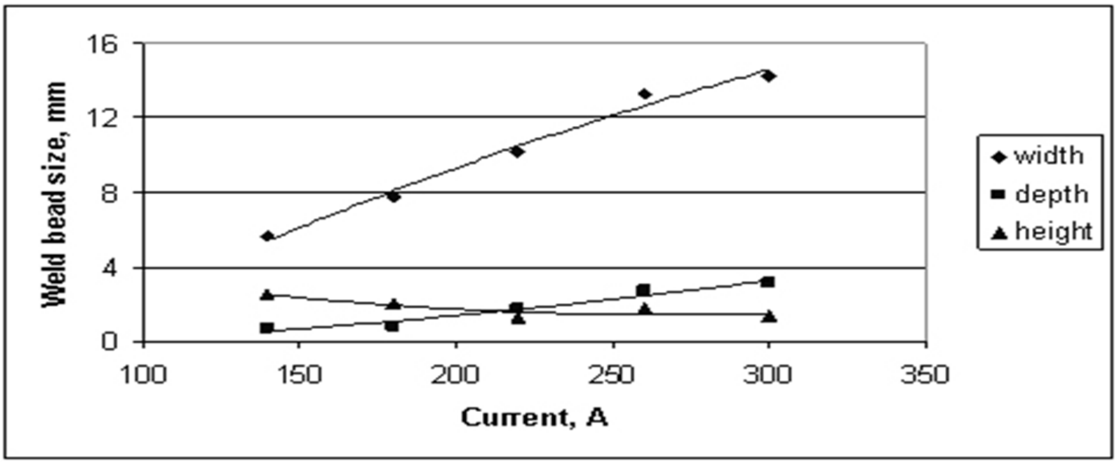


Fig. 3 : Variation of weld bead dimensions with welding current whilst other parameters remaining constant. Single weld bead made with conventional TIG welding at 80 mm/min welding speed and at a wire feeding speed of 910 m/min [3].

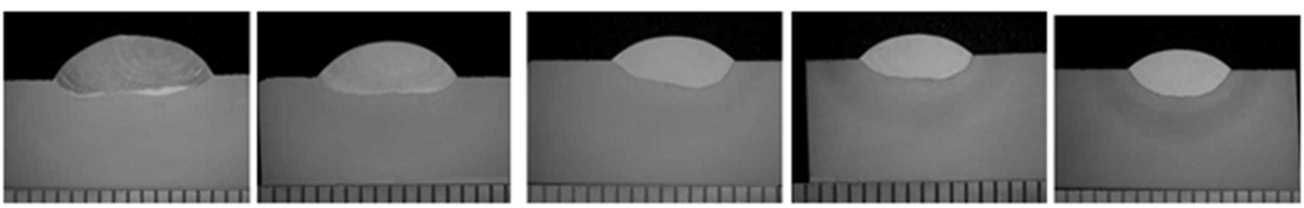


Fig. 4 : Photo macrographs of typical transverse sections of single weld bead produced by increasing welding speed. Note the different magnifications in the photographs [3].

Photo macrograph of typical transverse weld sections of single weld beads obtained by varying the welding speed are shown in below **Fig. 4**. The Variation in weld bead size with respect to welding speed is as shown in **Fig. 5**. The weld width decreases with increasing welding speed. The penetration depth remains the same, almost independent of the welding speed. The weld height showed a decrease with increasing welding speed.

Dilution less than 15% is obtained at current levels lower than 150A whereas the dilution is in excess of 50% for welding current in excess of 230A showing uncertainties with weld dilution for TIG welding process.

The dilution increases with increasing heat input when the increase in heat input is achieved through an increase in welding current at constant welding speed. However, the dilution decreases with increasing heat input when the increase in heat input is achieved through a reduction in welding speed at constant welding current. There is significant difference in dilution, for the same heat input depending on whether the heat input is achieved through control of the welding current or the welding speed. For example, at a heat input of 750J/m, dilution in the range 15-25% is achieved by controlling the welding current whilst 50-60% dilution is obtained by controlling the welding speed.

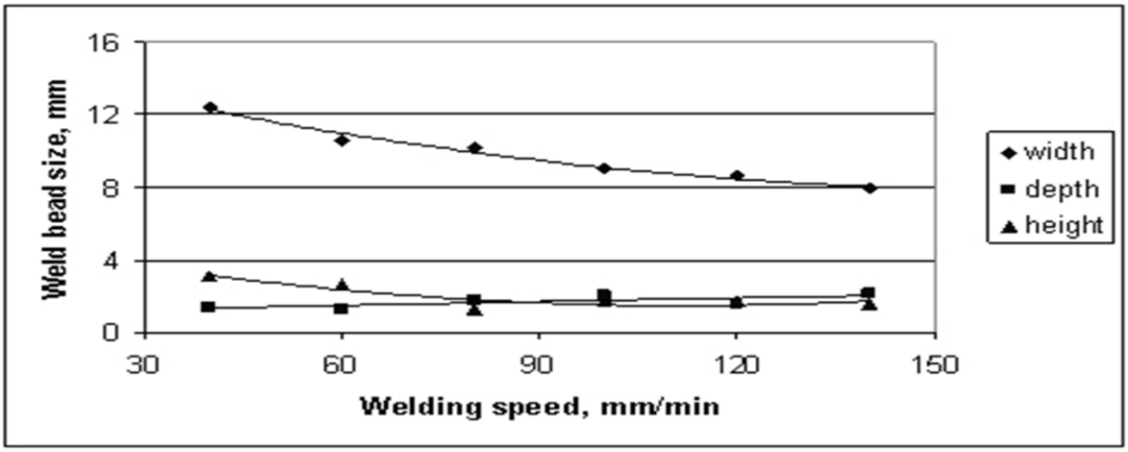


Fig. 5 : Variation of weld bead dimensions with welding speed whilst other parameters remaining constant. Single weld-bead made with conventional TIG welding at 220A welding current and at 910mm/min wire feeding rate [3].

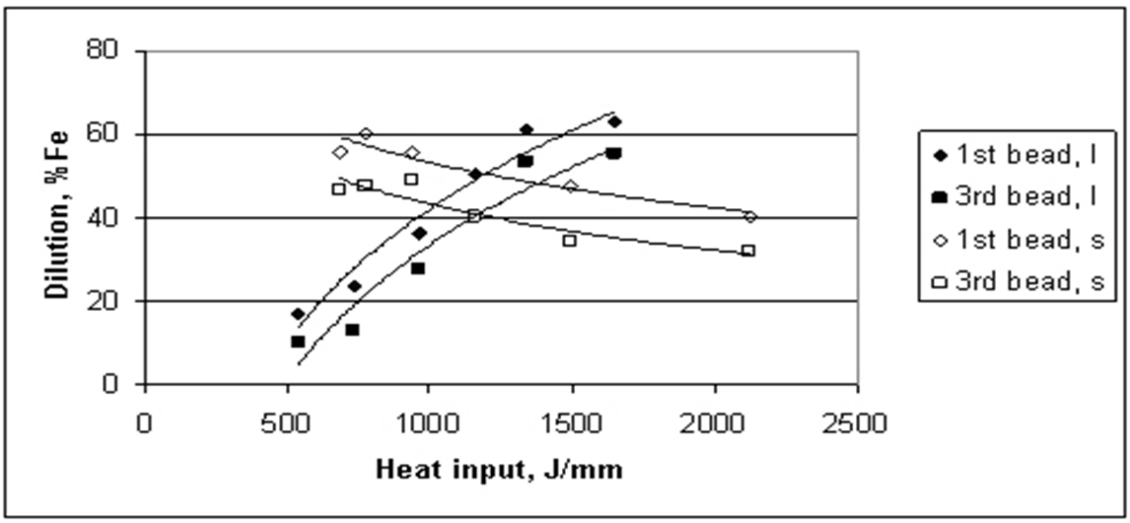


Fig. 6 : Variations in dilution of the 1st and 3rd bead with heat input obtained by varying welding current 'I' and welding speed 'S' with other welding parameters remaining constant [3].

Significant differences in dilution can be observed between the first weld bead and the subsequent beads. This is because, in the first bead, the arc directly strikes on the virgin base metal resulting in significantly higher melting of the parent metal. In subsequent overlapping weld passes, a part of the initial weld bead would be melted reducing the extent of parent metal melting, and a steady state would be reached after certain number of passes. Initial TIG welding experiments shows that the dilution reaches approximately steady state conditions on the third bead, hence for the subsequent welding experiments; the dilutions of the first and third weld beads are compared [3].

1.3 Effect of Wire Feed Rate and Melting Power on Dilution for GTAW

A research paper related to fusion welds between super austenitic stainless steel using Ni based filler metals using gas tungsten arc welding states that the dilution level can be correlated exclusively to the ratio of the volumetric filler metal feed rate (V_{fm}) to arc power (VI), i.e. the individual values of V_{fm} and VI are not important in controlling the dilution and resultant weld metal composition. It also states that for a given set of parameters, the total amount of power available for melting the base and filler metals is a fixed quantity. With an

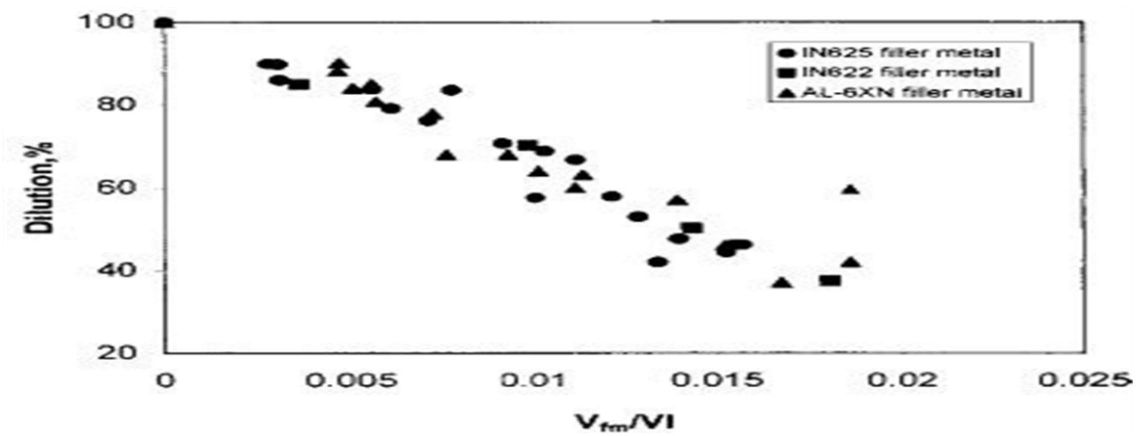


Fig. 7 : Dilution levels as a function of the ratio of volumetric filler metal feed rate to arc power [3].

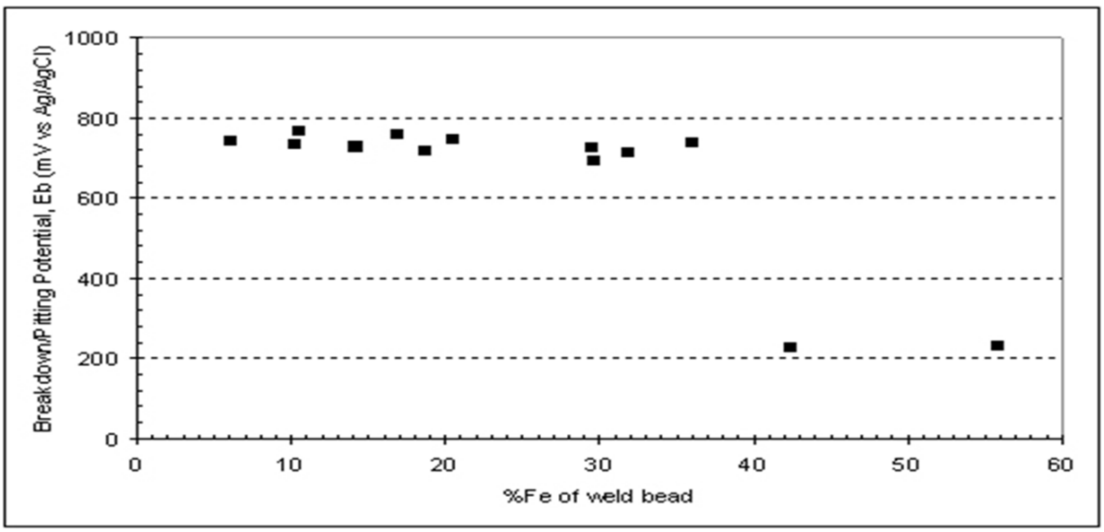


Fig. 8 : Relationship between breakdown potential and dilution (% Fe) in weldmetal for Inconel 625 [3].

increase in the volumetric filler metal feed rate, which does not change the amount of power available for melting, as VI and V_{fm} are independent parameters, a larger portion of the total melting power is required to melt the larger volume of deposited filler metal. So, less power is available for melting the substrate and the volumetric melting rate of the substrate decreases. Thus, dilution levels decreases as the filler metal feed rate increases, because a larger percentage of the fusion zone was composed of the filler metal. Conversely, the dilution levels are also altered by changing the amount of power available for melting through variation of the arc power. By decreasing the arc power while maintaining a fixed volumetric filler metal feed rate, the total amount of power available for melting decreases. This again reduces the volumetric melting rate of the substrate and, as a result, the dilution levels decreases with decreasing arc power. In brief, it can be stated that higher the volumetric feed rate to arc power ratio, lesser will be the dilution [2]. This is clearly concluded from **Fig. 7**.

1.4 Effect of Dilution on Corrosion Resistance

Fig. 8 shows the breakdown potential plotted against the degree of dilution represented by %Fe in the composition. It shows there is a marked reduction in the break down potential between 36 and 42% Fe which corresponds to a reduction of PREN from 33 to 29, where PREN is pitting resistance equivalent number given by formula below. Corrosion resistance decreases if dilution level goes beyond 36% in a specific environment. The study corresponds to Inconel 625 [3].

$$PREN = \%Cr + 3.3\%Mo + 16\%N$$

2.0 EXPERIMENTAL PROCEDURE

Studies were carried out for clad restoration using base material of SA 387 Gr. 11 Cl. 2 having clad of 410s as they are widely used for fabrication of a coke drum with mechanical properties as shown in **Table 3**. The chemical compositions of both the material are stated in **Table 2** and **Table 3** respectively.

Literature suggests AWS E/ER 309L or 430 filler material for the clad restoration of 410s [5]. As coke drums are operated at about 480°C to 490°C, material with high creep strength should be selected. As creep strength of Inconel is higher compare to stainless steel at that temperature, consumable of it should be used for clad restoration. Comparison of coefficient of thermal expansion is also shown below indicating that base metal is having almost same coefficient as that of Inconel while for stainless steel, it is lower which may lead to distortion causing cracking or improper corrosion resistance. And so, consumables of Inconel 182 (ENiCrFe – 3 for SMAW, dia. 2.5 & 3.2) and Inconel 82 (ERNiCr-3 for GTAW, dia. 1.2) were selected having microstructure same as Inconel 600 [6].

To ensure the compositions, chemical pads were prepared according to ASME 2013, Sec. II, Part C as shown in **Fig. 9**.

This study aims to achieve chemistry of Inconel 182 as per SFA 5.11 ASME 2013, Sec. II, part C, mentioned in below **Table 4** throughout 3 mm thickness of clad restoration by reducing the dilution, especially %Fe below 10 in flat & vertical uphill positions.

Table 1 : Mechanical properties of SA 387 Gr. 11 Cl.2 & 410S [4,5]

Sr. No.	Description	SA 387 Gr.11 Cl. 2	410S
1.	Tensile Strength, MPa	515-690	415
2.	Yield Strength, MPa	310	205
3.	Elongation in 2-inch, min. %	22	22

Table 2 : Alloying addition of SA-387 Gr.11 Cl.2[a] [4]

Element	C	Mn	P	S	Si	Cr	Mo	Fe
% Range	0.04-0.17	0.35-0.73	0.0025	0.0025	0.44-0.86	0.94-1.56	0.40-0.70	Bal.

a - Single values are maximum one.

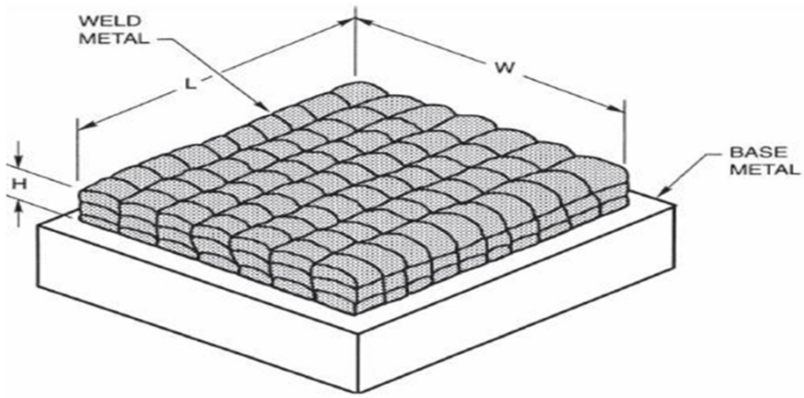
Table 3 : Typical composition of 410S Clad[a] [5]

Element	C	Mn	P	S	Si	Cr	Mo	Fe
% Range	0.08	1.00	0.04	0.03	1.00	11.5-13.5	0.6	Bal.

a - Single values are maximum one.

Table 4 : Coefficient of thermal expansion at elevated temperatures [7].

Material	Coefficient of Thermal Expansion (CTE X 10^{-6} mm/mm°C)	
	475°C	500°C
SA 387 Gr. 11 Cl. 2	14.2	14.4
Ferritic Stainless Steel	13.0	13.1
Inconel 600	14.7	14.8



Electrode Size			Weld Pad Size	
in.	mm		in., min.	mm, min.
5/64 3/32 — 1/8	2.0 2.4* 2.5 3.2	L = W = H =	1-1/2 1-1/2 1/2	38 38 13
5/32 3/16 — 1/4	4.0 4.8* 5.0 6.4*	L = W = H =	2 2 7/8	50 50 22

*Metric sizes not shown in ISO 544.

Fig. 9 : Pad for chemical analysis of undiluted weld metal with pad dimensions [8]

Table 5 : Chemical composition requirement for undiluted weld metal according to ASME 2013, Sec. II, part C [8].

Element	C	Mn	P	S	Si	Cu	Ni	Ti	Cr	Nb	Fe
% Range	0.1	5.0-9.5	0.03	0.015	1.00	0.5	59(min)	1.0	13-17	1-2.5	10

The available possibilities to decrease dilution are

- Selection of electrode or filler with least % Fe.
- Increase in bead thickness.
- Increase in bead overlap.
- Use of layer by layer grinding.
- For GTAW, increasing wire feed rate to arc power ratio.

The experiments which were decided from above points are:

Experiment A: (for SMAW with overlap of 50%)

1. Lower current & lower travel speed/bead length.
2. Lower current & higher travel speed/bead length.
3. Higher current & lower travel speed/bead length.
4. Higher current & higher travel speed/bead length.

Experiment B: (for SMAW)

Trials with overlap 50%, 60% & 70%.

Experiment C: (for SMAW)

Depositing barrier layer was deposition with 3.2 mm diameter electrode, grinding the barrier layer to ½ thickness and then subsequent layers' deposition with 2.5 mm diameter electrodes.

Experiment D: (for mechanized GTAW)

Effect of wire feed rate and current on dilution was to be evaluated.

Some considerations were as follows:

1. Experiments A, B and C were carried out in two positions flat & vertical uphill with electrode diameters 2.5 and 3.2 mm for SMAW only.
2. Experiment D was carried out only using GTAW – machine in flat position.
3. Preheat temperatures for barrier layer and subsequent layers were 125°C and 20°C respectively while interpass temperature was 175°C for both SMAW and GTAW.

2.1 Weld Joint Preparation

The clad plates with thickness of clad 3 mm on the base metal with thickness about 40 mm were used for experimental work with edge preparation as shown in **Fig. 10**. After joint preparation, $CuSo_4$ test was done to ensure presence of base metal over which clad restoration was to be done.

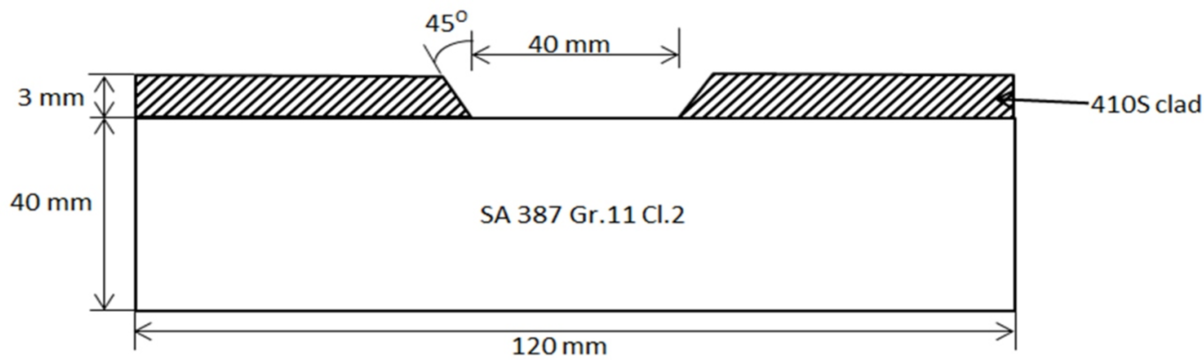


Fig. 10 : Weld joint preparation for experimental work.

2.2 Selection of Parameters

Parameter selection was done based on data available from manufacturer & on the past experience for INCONEL 182, which are described in **Tables 6 (1 to 4).**

- ENiCrFe-3 used was of 2.5 mm dia. x 300 mm (L) and 3.15 mm dia. x 350 mm (L).
- ERNiCr-3 used was of 1.2 mm diameter.

Parameters selected for SMAW in flat and vertical uphill positions are as shown in **Table 6(1)** for experiment A with 24V and overlap 50%. For experiment B with both positions, parameters are as shown in **Table 6(2)**. For experiment C, parameters are as shown in **Table 6(3)**.

Parameters selected for GTAW in flat position are as shown in **Table 6(4)** for experiment D in which wire feed rate and current were varied. Other parameters for GTAW trials are as follow.

- Position: 1G
- Voltage: 18 Volts
- Travel speed: 140 mm/min
- Polarity: DCEN
- Filler metal dia.: 1.2 mm
- Filer metal delivery: from leading edge of the torch
- Contact tube to work distance: 10 mm
- Electrode (Dia.): EWTh-2 (Φ 2.4 mm)
- Shielding gas flow rate: Ar (20-25 LPM)
- Overlap: 50%

Table 6(1) : Parameters used for ENiCrFe-3 for Experiment A.

Parameters	Flat		Vertical Uphill	
	Current (A)	Bead Length (mm)	Current (A)	Bead Length (mm)
For 2.5 x 300 mm				
Lower current & lower bead length	50-55	100-110	50-55	75-85
Lower current & higher bead length	50-55	175-185	50-55	125-135
Higher current & lower bead length	65-70	100-110	65-70	100-110
Higher current & higher bead length	65-70	175-185	65-70	125-135
For 3.15 x 350 mm				
Lower current & lower bead length	70-75	80-90	70-75	70-80
Lower current & higher bead length	70-75	150-160	70-75	120-130
Higher current & lower bead length	100-105	80-90	85-90	70-80
Higher current & higher bead length	100-105	150-160	85-90	120-130

Table 6(2) : Parameters used for ENiCrFe-3 for Experiment B.

Parameters	Flat		Vertical Uphill	
	Current (A)	Voltage (V)	Current (A)	Voltage (V)
For 2.5 x 300 mm				
Overlap of 50%, 60% & 70%	60-65	24	55-60	24
For 3.15 x 350 mm				
Overlap of 50%, 60% & 70%	80-85	24	75-80	24

Table 6(3) : Parameters used for ENiCrFe-3 for experiment C.

Parameters	Flat		Vertical Uphill	
	Current (A)	Voltage (V)	Current (A)	Voltage (V)
For 2.5 x 300 mm				
2.5 mm diameter	60-65	24	60-65	24
For 3.15 x 350 mm				
2.5 mm diameter	80-85	24	70-75	24

Table 6(4) : Parameters used for ERNiCr-3 for experiment D.

Wire Feed Rate (m/min)	Current (A)			
	160	175	185	200
2.0	Exp.31	Exp.32	Exp.33	Exp.34
2.2	Exp. 35	Exp.36	Exp. 37	Exp. 38
2.4	Exp. 39	Exp. 40	Exp. 41	Exp. 42
2.6	Exp. 43	Exp. 44	Exp. 45	Exp. 46
2.8	Exp. 47	Exp. 48	Exp. 49	Exp. 50

3.0 RESULTS

3.1 Chemical Analysis of Consumables

Chemical pads, as per ASME Sec II, part C, were prepared to verify the chemistry of selected batch of consumables. **Table 7** indicates the observations of chemical analysis of the pads prepared, meeting the requirements.

3.2 Results of Experiment A

Table 8(1-2) show results for experiment A for dia. 2.5 and 3.15 respectively.

Dilution calculated using equation (a) is reported as analytical value in the table while dilution calculated using %Fe (using chemical equation given in (b)) is reported as chemical value for the comparison purpose.

Fig. 11 to **Fig. 14** show concentration profiles for said experiments; it is evident that undiluted clean chemistry is not achieved through out thickness or even at the surface of overlay for any of the experiment.

Table 7 : Chemistry obtained for chemical pads prepared as per ASME 2013, Sec. II, Part C.

Sr. No.	Description	Dia.	Fe	C	Mn	Cr	Ni
Requirements (%)			**10**	**0.1**	**5.0-9.5**	**13-17**	**59$_{(min)}$**
1.	ENiCrFe-3, Batch 1	2.5 mm	5.95	0.024	6.71	16.20	67.66
2.	ENiCrFe-3, Batch 2	2.5 mm	6.03	0.019	6.21	15.00	66.46
3.	ENiCrFe-3	3.15 mm	3.47	0.041	7.35	16.43	67.56
4.	ERNiCr-3	1.2 mm	0.64	0.018	3.01	14.26	70.33

Table 8(1) : Results of experiment A – ENiCrFe - 3 for 2.5 mm dia. electrodes.

Description	Flat				Vertical Uphill			
	Exp. 1	Exp. 2	Exp. 3	Exp.4	Exp.5	Exp. 6	Exp.7	Exp.8
% Fe at surface	11.23	10.43	16.21	14.68	11.13	14.47	14.26	13.83
% Dilution $_{(ana.)}$	24.84	26.75	25.42	26.67	28.41	36.54	27.97	32.5
% Dilution$_{(chem.)}$*	23.89	30.48	38.95	31.29	18.37	19.35	28.93	25.71
Depth of Weld Interface (mm)	1-1.5	1-1.5	1-1.5	1-1.5	1-1.5	1.5-2	1.5-2	1-1.5
Thk (from finished s/f) at which other elements are met except %Fe (mm)	1.0	2.0	1.0	1.0	2.5	2.5	1.5	2.5

*Dilution using chemical formula, is calculated and reported at weld interface.

Table 8 (2) : Results of Experiment A –ENiCrFe -3 for 3.15 diameter electrodes.

Description	Flat				Vertical Uphill			
	Exp. 9	Exp.10	Exp.11	Exp.12	Exp.13	Exp. 14	Exp.15	Exp.16
% Fe at surface	10.15	11.61	14.54	12.25	14.5	12.43	16.31	16.98
% Dilution $_{(ana.)}$	34.58	35.13	37.13	28.96	38.37	59.12	33.8	45.8
% Dilution$_{(chem.)}$	24.70	27.59	29.64	30.81	40.02	30.33	42.42	34.65
Depth of Weld Interface (mm)	1.5-2	1.5-2	1.5-2	1.5-2	1-1.5	1-1.5	1.5-2	1.5-2
Thk (from finished s/f) at which other elements are met except %Fe (mm)	2.5	2.0	0.5	2.0	0.5	1.5	0.0	0.0

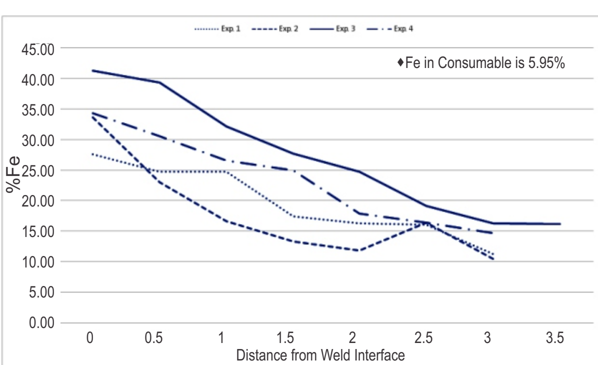


Fig. 11 : Concentration Profiles of Fe for Experiment A – Dia. 2.5 mm, Flat Position.

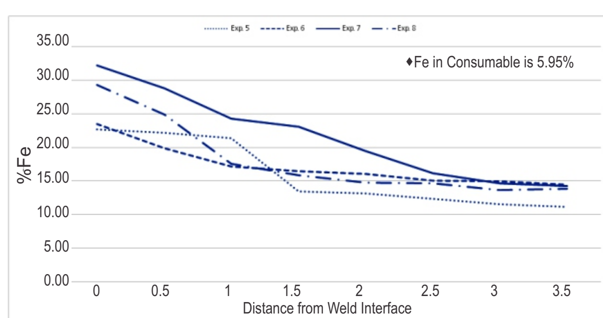


Fig. 12 : Concentration Profiles of Fe for Experiment A – Dia. 2.5 mm, Vertical Uphill Position.

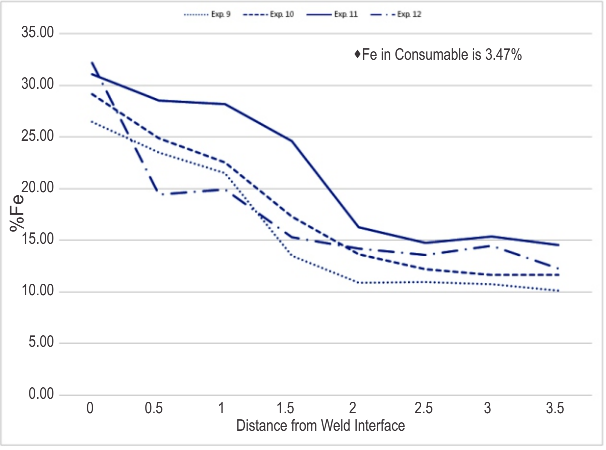


Fig. 13 : Concentration Profiles of Fe for Experiment A – Dia. 3.15 mm, Flat Position.

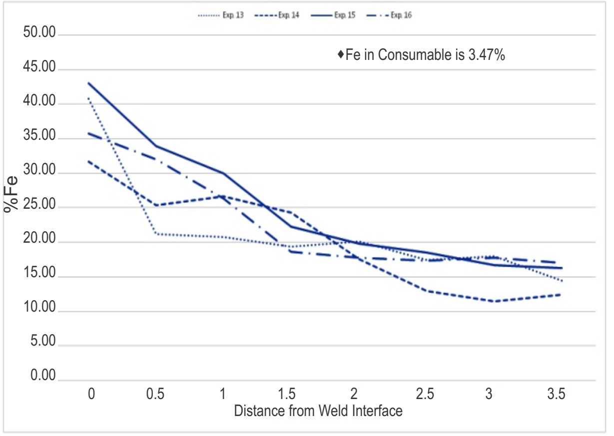


Fig. 14 : Concentration Profiles of Fe for Experiment A – Dia. 3.15 mm, Vertical Uphill Position.

3.3 Results of Experiment B

Observations are reported in **Table 9(1) & 9(2)**. Dilution values calculated using analytical and chemical equations are also reported.

Table 9(1) : Results of experiment A – ENiCrFe - 3 for 2.5 mm dia. electrodes.

Description	Flat			Vertical Uphill		
	Exp.17	Exp.18	Exp.19	Exp.20	Exp.21	Exp. 22
% Fe at Surface	9.85	7.44	7.27	10.85	11.78	8.54
% Dilution $_{(ana.)}$	23.64	21.81	15.15	27.00	22.23	17.23
% Dilution$_{(chem.)}$	13.02	8.78	7.28	24.44	29.27	8.37
Depth of Weld Interface (mm)	0-0.5	0-0.5	0.5-1	0.5-1	0.5-1	0.5-1
Thk (from finished s/f) at which other elements are met except %Fe (mm)	2.5	3.0	3.0	2.5	1.0	3.0

Table 9(2) : Results for Experiment B – ENiCrFe – 3 for 3.15 mm dia. electrodes.

Description	Flat			Vertical Uphill		
	Exp.23	Exp.24	Exp.25	Exp.26	Exp.27	Exp. 28
% Fe at Surface	9.34	8.84	8.79	10.42	13.4	8.54
% Dilution $_{(ana.)}$	9.93	9.52	12.19	22.48	26.23	30
% Dilution$_{(chem.)}$	32.49	30.68	24.81	75.41	39.12	76.91
Depth of Weld Interface (mm)	1-1.5	1-1.5	0.5-1	1-1.5	1-1.5	1-1.5
Thk (from finished s/f) at which other elements are met except %Fe (mm)	1.5	1.0	1.5	0.5	1.0	2.0

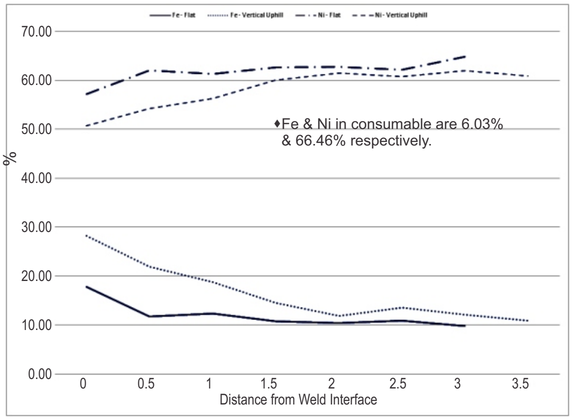


Fig. 15 : Concentration Profiles for Experiment B – Dia. 2.5 mm, 50% Overlap.

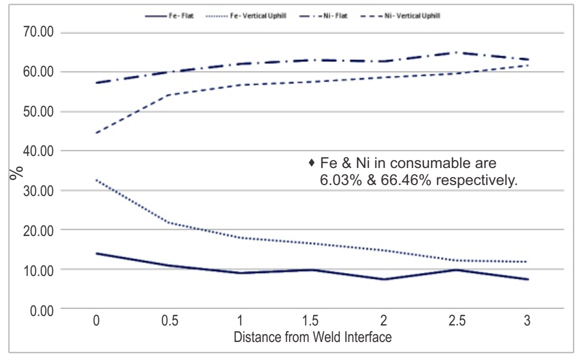


Fig. 16 : Concentration Profiles for Experiment B – Dia. 2.5 mm, 60% Overlap.

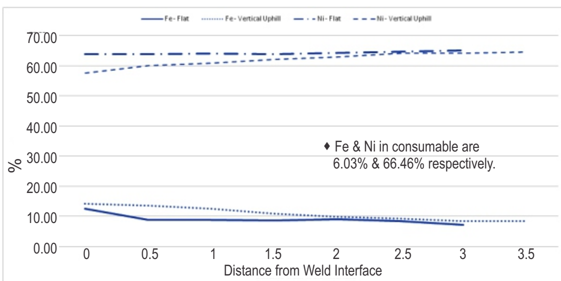


Fig. 17 : Concentration Profiles for Experiment B – Dia. 2.5 mm, 70% Overlap.

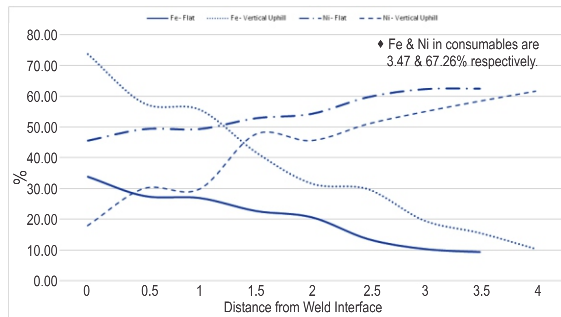


Fig. 18 : Concentration Profiles for Experiment B – Dia. 3.15 mm, 50% Overlap.

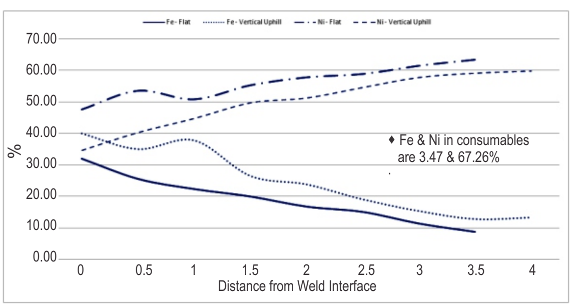


Fig. 19 : Concentration Profiles for Experiment B – Dia. 3.15 mm, 60% Overlap.

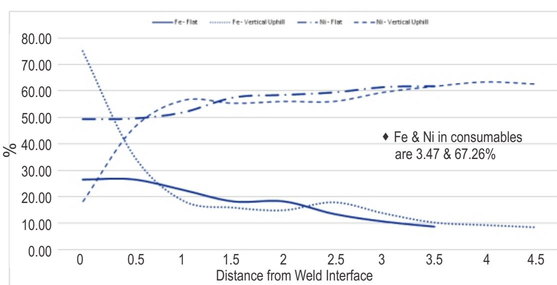


Fig. 20 : Concentration Profiles for Experiment B – Dia. 3.15 mm, 70% Overlap.

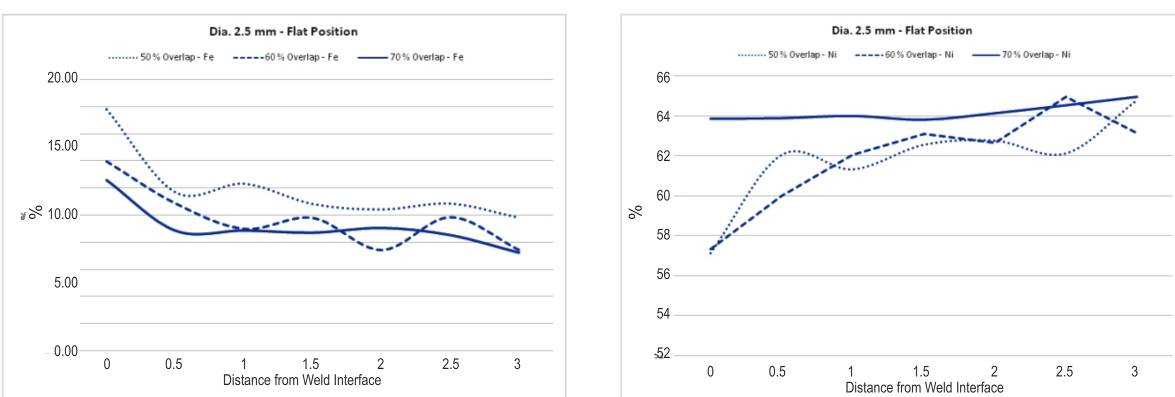


Fig. 21 (a) & (b) : Concentration profiles comparison for 50, 60 & 70% Overlap – Flat position, Dia. 2.5 mm.

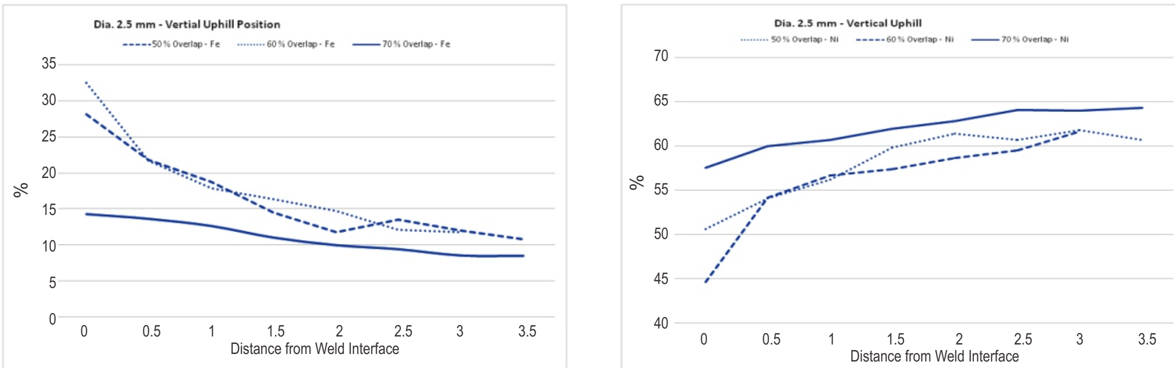


Fig. 22 (a) & (b) : Concentration profiles comparison for 50, 60 & 70% Overlap – Vertical Uphill position, Dia. 2.5 mm.

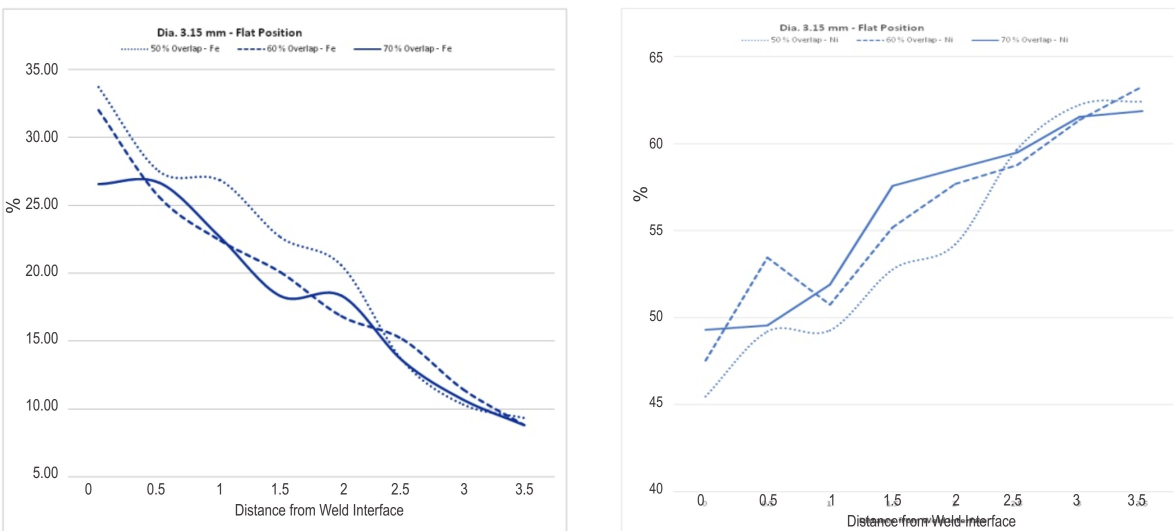


Fig. 23 (a) & (b) : Concentration profiles comparison for 50, 60 & 70% Overlap – Flat position, Dia. 3.15 mm.

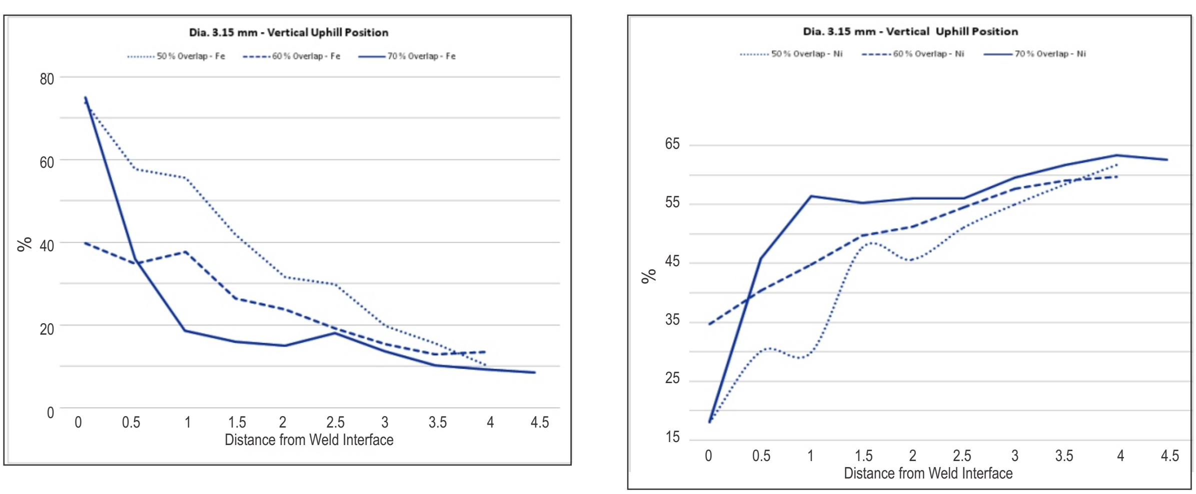


Fig. 24 (a) & (b) : Concentration profiles comparison for 50, 60 & 70% Overlap – Vertical Uphill position, Dia. 3.15 mm.

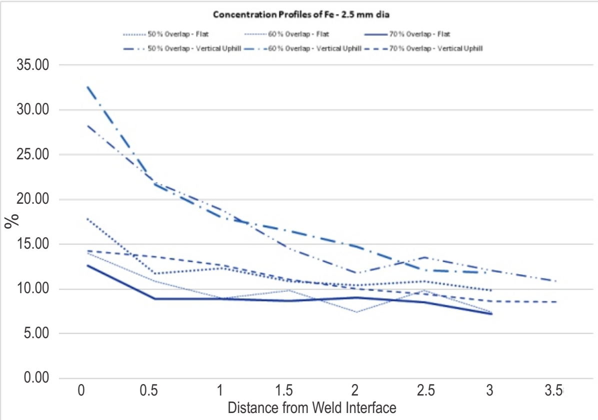


Fig. 25 : Concentration profiles of Fe - 2.5 mm dia.

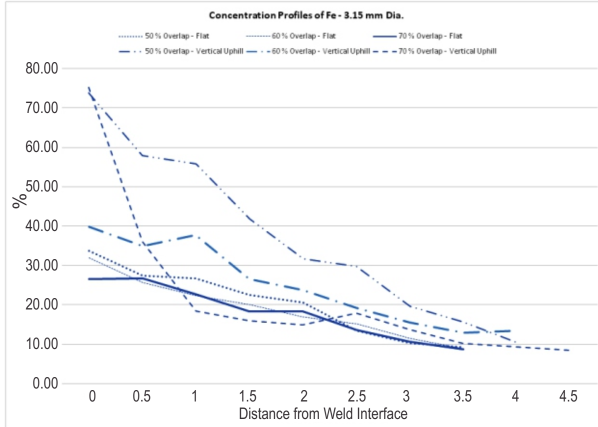


Fig. 26 : Concentration profiles of Fe - 3.15 mm dia.

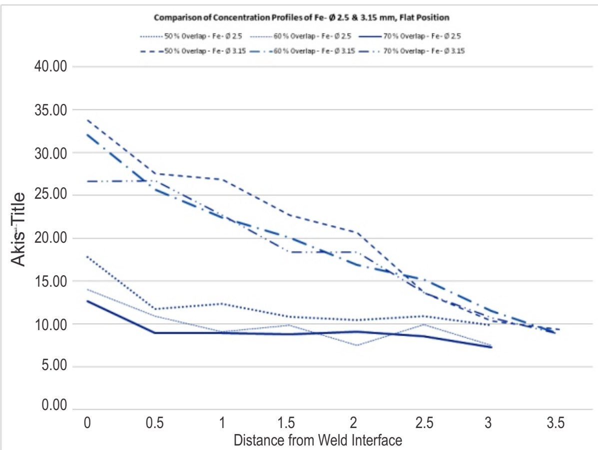


Fig. 27 : Comparison of concentration profiles of Fe – 2.5 & 3.15 mm dia., Flat position.

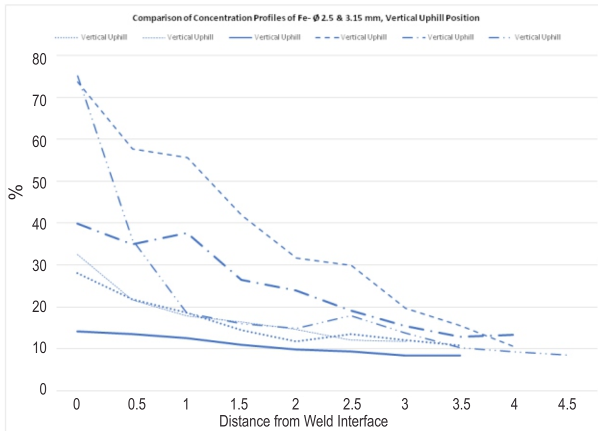


Fig. 28 : Comparison of concentration profiles of Fe – 2.5 & 3.15 mm dia., Vertical Uphill position.

Concentration profiles for above experiments are shown in **Fig. 15** to **28**. The said profiles & their comparisons provide following observations.

- Dilution is more in vertical uphill position compare to flat position.
- With increase in overlap, lesser would be Fe and higher would be Ni in deposited weld metal.
- As the % overlap increases, the average slope of concentration profile decreases showing small change in composition of filler metal while being deposited as a weld.
- Increase in overlap is not helpful to reduce dilution at weld interface but helps to achieve chemistry at increasing distance from weld interface for the constant diameter of electrode.
- Reduction of electrode diameter plays a major role to decrease dilution for both flat and vertical uphill positions.

From chemical profiles shown above, undiluted clean chemistry requirement is achieved using Inconel 182 electrode of 2.5 mm diameter with 70% overlap in flat position but for remaining experiments, undiluted clean chemistry requirements cannot be achieved throughout the weld overlay thickness of 3 mm although %Fe at surface, is below 10 for each experiment carried out in flat position and with 70% overlap in vertical uphill position.

3.4 Results of Experiment C

Table 10 reports results for experiment C while concentration profile is shown in **Fig. 29**.

Table 10 : Results for Experiment C – ENiCrFe - 3 electrode.

Parameters	Flat		Vertical Uphill	
	Barrier Layer (Φ 3.15 mm)	Subsq. Layer (Φ 2.5 mm)	Barrier Layer (Φ 3.15 mm)	Subsq. Layer (Φ 2.5 mm)
% Fe at Surface	9.41		9.49	
% Dilution (ana.)	32.8		33.8	
% Dilution(chem.)	34.65		41.67	
Depth of Weld Interface (mm)	1-1.5		1-1.5	
Thk (from finished s/f) at which other elements are met except %Fe (mm)	1.5		2.0	

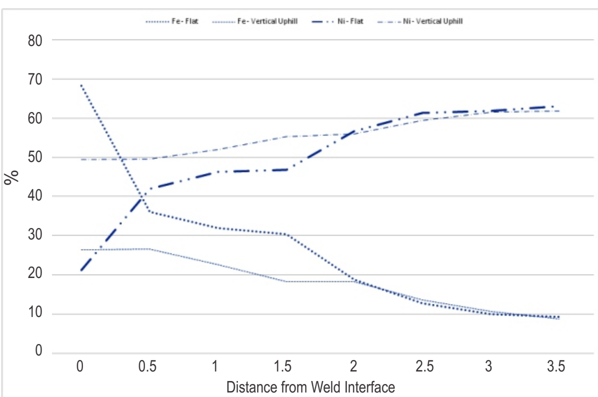


Fig. 29 : Concentration profiles for Experiment C.

It can be observed from the concentration profiles that undiluted clean chemistry is not achieved for the entire overlay thickness of 3 mm but % Fe below 10 is obtained at finished surface.

3.5 Results of Experiment D

In these experiments, variations were done with variation in wire feed rate and current. **Table 11** shows the % Fe at surface. Although %Fe was below 10 in each trial, it was not possible to achieve undiluted clean chemistry in every trial. Depth of fusion for the trials in which undiluted clean chemistry was achieved was in the range of 0.5-1 mm. **Table 12** shows dilution values based on analytical formula and **Table 13** shows dilution values based on chemical formula.

Table 11 : %Fe at surface for experiment D with ERNiCr-3 of 1.2 mm dia

Wire Feed Rate (m/mm)	Current (Amps)			
	160	175	185	200
2.0	5.23	7.36	5.76	7.07
2.2	3.96	7.13	5.95	8.58
2.4	9.55	4.05	5.57	7.12
2.6	2.06	5.97	5.64	6.79
2.8	1.06	6.58	3.33	3.18

Table 12 : Analytical dilution values for experiment D with ERNiCr-3 of 1.2 mm dia.

Wire Feed Rate (m/mm)	Current (Amps)			
	160	175	185	200
2.0	9.09	15.58	23.18	24.70
2.2	5.83	19.68	11.76	22.01
2.4	7.69	19.24	17.35	20.53
2.6	5.93	17.12	20.91	16.08
2.8	4.67	18.12	17.88	10.11

Table 13 : Chemical dilution values for experiment D with ERNiCr-3 of 1.2 mm dia.

Wire Feed Rate (m/mm)	Current (Amps)			
	160	175	185	200
2.0	21.18	31.17	79.64	37.27
2.2	52.40	14.15	37.44	19.58
2.4	52.40	31.71	85.92	15.33
2.6	10.22	6.60	7.06	21.45
2.8	7.76	5.81	6.49	4.84

Table 14 : Thickness (from finished surface) at which other elements are met except %Fe (mm)

Wire Feed Rate (m/mm)	Current (Amps)			
	160	175	185	200
2.0	1.5	2.5	2.5	2.5
2.2	3.0	3.0	3.0	3.0
2.4	2.5	3.0	2.5	3.0
2.6	All elements meet requirements			3.0
2.8				3.0

Although % Fe at surface was below 10 in each trial, it was not possible to achieve undiluted clean chemistry in each trial. Undiluted clean chemistry was achieved in experiment number 43, 44, 45 (wire feed rate 2.6 m/min. & current 160A, 170A & 185A respectively) and in experiment numbers 47, 48, 49 (wire feed rate 2.8 m/min. & current 160A, 170A & 185A respectively) along with presence of lack of fusion.

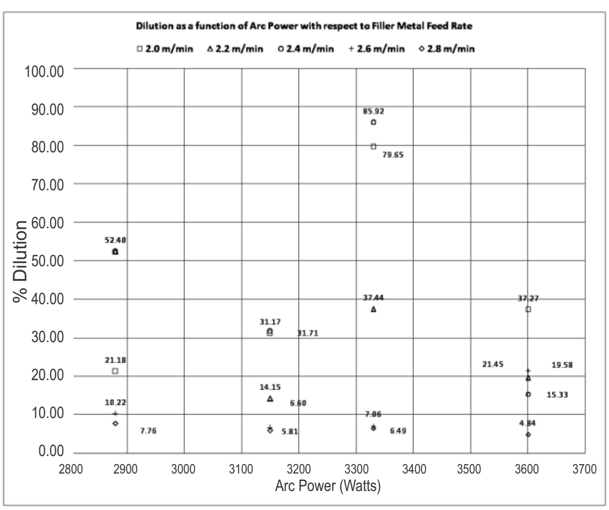


Fig. 30 : Dilution as a function of Arc Power with respect to Filler Metal Feed Rate.

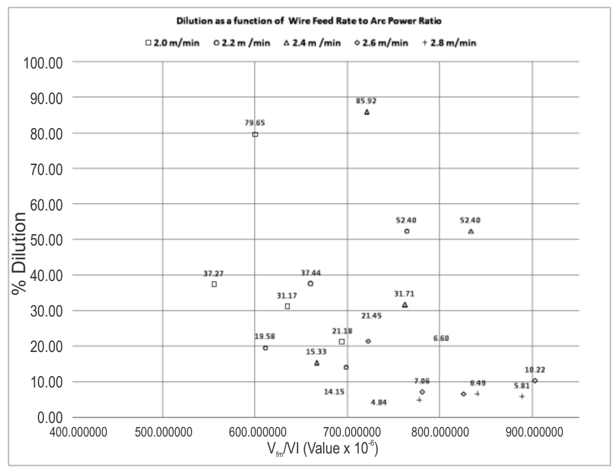


Fig. 31 : Dilution as a function of Wire Feed Rate to Arc Power Ratio.

Both **Fig. 30 & Fig. 31** show the plot of dilution values for experiment D calculated using chemical formula as a function of arc power with respect to filler metal feed rate and as a function of wire feed rate to arc power ratio. It can be observed that with increasing ratio of wire feed rate to melting power, dilution decreases.

3.6 Corrosion Examination

To identify the effect of variation in dilution giving different % Fe in weld bead on the corrosion resistance for which Inconel 600 is deposited in the coke drum, samples with different %Fe, were kept under corrosion testing i.e. ASTM G28 method A as well as cyclic polarization. Observations for are shown in **Table 15** and **16** respectively.

Table 15 : Corrosion examination observations for Inconel 600 with varying %Fe examined by ASTM G28 Method A.

Sr.. No.	Average % Fe	Initial Wt. (gms)	Final Wt. (gms)	Wt. Loss (gms)	Surface Crea (cm^2)	Rate of Corrosion (mpy)
1.	17.86	8.5655	8.5597	0.0058	12.7342	7.7851
2.	10.71	7.2919	7.2884	0.0035	11.7692	5.0831
3.	7.04	10.3033	10.3010	0.0023	13.6437	2.8814
4.	1.86	8.8926	8.8917	0.0009	12.2103	1.2599

Table 16 : Corrosion examination observations for Inconel 600 with varying %Fe examined by cyclic polarization

Sr. No.	Average % Fe	$I_{corr.}$ (μa)	$E_{corr.}$ (mV)	$E_{rp.}$ (mV)	Rate of Corrosion (mpy)
1.	17.86	36.00	-459.00	38.25	54.06
2.	10.71	11.70	-402.00	16.42	17.48
3.	7.04	0.707	-424.00	-175.4	1.06
4.	1.86	0.640	-488.00	-66.68	0.96

Following **Fig 32** show the tafel curves for various samples having % Fe as shown in the **Table 15 & 16**.

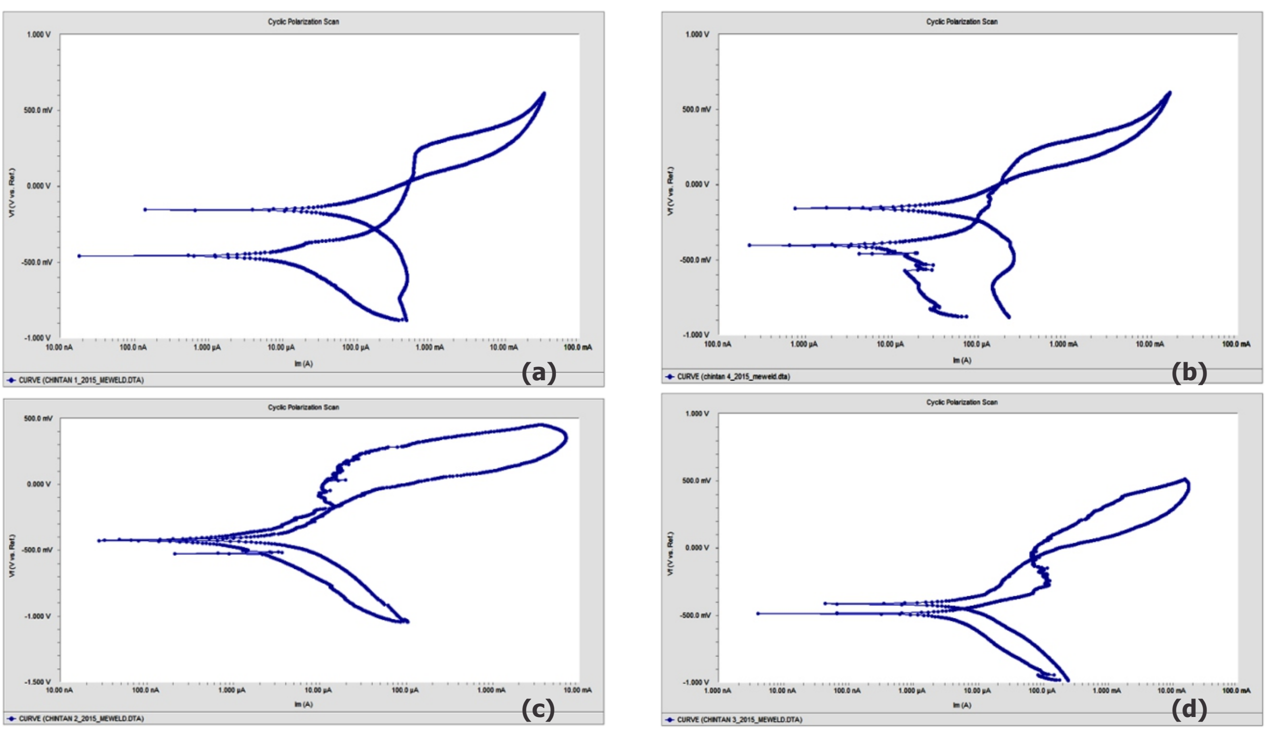


Fig. 32 : Tafel curves for average %Fe (a) 17.86 (b) 10.71 (c) 7.04 & (d) 1.86.

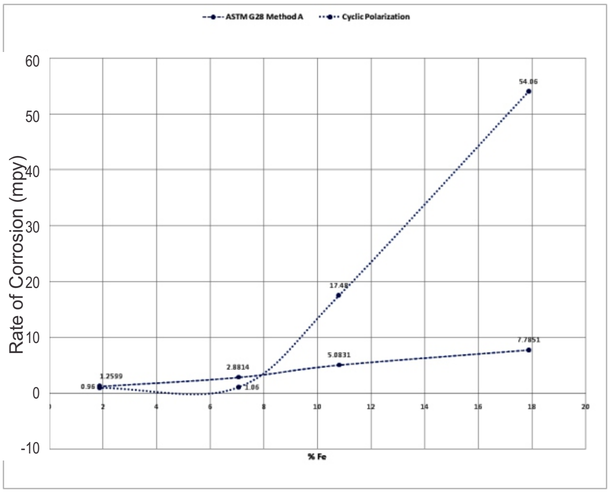


Fig. 33 : Corrosion Rate with respect to %Fe in Weld Overlay of Inconel 600

As the average %Fe decreases from 17.86 to 1.86 in weld overlay, corrosion rate decreases from 7.79 to 1.26 mpy for ferric sulphate - sulphuric acid environment and in 3% sodium chloride environment, it decreases from 54.06 to 0.96 mpy, justifying the requirement of dilution control in clad restoration to ensure the corrosion resistance at elevated temperature as clearly shown in the graph.

4.0 CONCLUSION

Following points can be concluded from various experiments:

- It is possible to achieve undiluted clean chemistry for 3 mm thickness using 2.5 mm diameter Inconel 182 electrode with 70% overlap in flat position for SMAW and using 2.6 to 2.8 m/min wire feed rate along with current range of 160 to 185 A at travel speed of 140 mm/min for GTAW.
- It is possible to achieve undiluted clean chemistry at surface with modification in welding parameters for 50%, 60% and 70% overlap in flat position and 70% overlap in vertical uphill position along with using layer by layer grinding for Inconel 182 but it is not possible to achieve it throughout the thickness. For Inconel 82 filler metal, wire feed rate of 2.0 to 2.4 m/min with current range of 160 to 200 A and feed rate of 2.6 to 2.8 m/min with current of 200 A also give the same results.
- Reduction in electrode diameter plays a major role in reduction of dilution for both positions.
- With increase in overlap, the weld metal chemistry tends to move towards filler metal chemistry.
- For GTAW process, filler metal feed rate & melting power individually do not contribute in reducing the effect of dilution however optimizing their combination yield required results.
- With achievement of 3 mm undiluted clean chemistry, the corrosion rate drastically reduces to 1.26 mpy from 7.79 mpy in case of exposure to ferric sulphate - sulphuric acid environment and for sodium chloride environment reduces to 0.96 from 54.06 mpy for which undiluted clean chemistry is not achieved.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support received from M/s Larsen & Toubro Ltd. & The M.S. University throughout the study.

REFERENCES

[1] Blondeau R (Editor) (2008), Metallurgy and Mechanics of Welding, Wiley & Sons, pp. 136-138.

[2] Banovic SN, Dupont JN and Marder AR (December, 2001), Dilution Control in Gas-Tungsten-Arc Welds Involving Superaustenitic Stainless Steels and Nickel-Based Alloys, Metallurgical and Materials Transactions B, pp. 1171-1176.

[3] Kumar V, Lee C, Verhaeghe G and Raghunathan S, CRA (2010), Weld Overlay -Influence of welding process and parameters on dilution and corrosion resistance, Stainless Steel World America, Huston, Texas, USA, pp. 1-6.

[4] ASME (2013), Boiler & Pressure Vessel Code, Sec. II, Part A, Ferrous Material Specifications, pp. 723-728.

[5] Sand Meyer Steel Company (June, 2014), Specification Sheet: Alloy 410s, sandmeyersteel.com, pp.1-2

[6] Nickel Development Institute (1994), Guidelines for the welded fabrication of nickel alloys for corrosion-resistant cervices, pp.9

[7] ASME (2013), Boiler & Pressure Vessel Code, Sec. II, Part D, Properties, pp. 753, 755, 763.

[8] ASME (2013), Boiler & Pressure Vessel Code, Sec. II, Part C, Specifications for Welding Rods, Electrodes and Filler metals, pp. 310, 316.