Experimental study on effect of flux composition on element transfer during submerged arc welding

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Abstract. The effects of flux composition on transfer of the elements have been studied through developed agglomerated fluxes on mild steel plates. The elements transferred to the welds have been shown in terms of a delta (Δ) quantity, which may be positive, negative or zero depending upon the composition of flux, wire and base plate. Carbon and manganese contents both show negative Δ quantity for most of the welds, indicating that both have been transferred from the weld metal to the slag. The results of this study show that for most of the welds, desulphurization and removal of phosphorus have been reported. The amount of element transferred is different for different welds depending upon the flux composition, dilution and slag metal reactions. Response surface methodology has been used for developing models for element transfer. The suggested model has been given for sulphur transfer to the weld. In this study the transfers of carbon, manganese, sulphur, phosphorus, silicon and nickel have been studied.

Keywords. Submerged arc welding; basicity index; element transfer; slag metal reactions; oxidizing power of the flux.

1. Introduction

Fluxes are used in submerged arc welding (SAW) to improve arc stability, to refine the weld metal and to add the alloying elements [1, 2]. Different ingredients in the flux provide different weld metal properties. The transfer of alloying elements during SAW depends on the physical and chemical properties of the fluxes. For correlating the properties with the composition of the weld it is necessary to understand the interaction between metal and flux because it will decide the extent of element transfer to the weld. To understand the mechanism of elements transfer during SAW is very difficult because the reactions involved in the weld pool and arc column are of very complex nature. The final weld metal composition in SAW depends upon the slag metal reactions, dilution, base plate composition and wire used [3]. As slag metal reactions play a major role in deciding final weld metal composition during SAW, much work is required to understand the transfer of elements from the flux [4]. As the reactions during SAW are very fast and the temperature involved is very high, it is

uncertain that the equilibrium has been achieved [5]. Hence, to determine the final weld metal composition, the kinetic and chemical factors that are responsible for elements transfer must be clearly understood.

When a slag is placed in contact with an iron alloy, an instantaneous equilibrium is established at the interface and FeO is formed [6, 7]. The chemical potential of the FeO is governed by the slag, metal compositions, equilibrium constant and diffusion coefficients. This chemical potential has a strong influence on weld pool chemistry. The electrochemical reactions can be more influential in metallic additions to the weld from the slag than thermochemical reactions [8, 9]. Frost *et al* [10] demonstrated electrochemical effect through chemical analysis of the electrode tip, detached droplets and the weld metal as a function of travel speed of the weld pool. Besides these, the concentrations of elements such as carbon, sulphur and phosphorus are higher in molten state than in the solid so that there is a tendency for these elements at the solid-liquid boundary [6]. Basicity index (BI), which is defined as the ratio of basic oxides to the acidic oxides, is commonly used as a measure of expected weld oxygen content. This BI also affects the elements transfer, as the various elements like carbon and

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manganese react with the available oxygen in the weld. Eagar [11] found that weld metal oxygen is reduced by increasing BI of the flux. The role of inclusions in the weld or slag is also decided by the flux constituents [12, 13].

In SAW, a molten drop after detaching from the electrode passes through high-temperature plasma and during this travel it reacts with various ions present in the plasma. The reactivity of ions with the droplet depends upon the flux composition, wire and base plate composition. After the arc has passed the high-temperature, stirring in the weld pool keeps the molten metal in intimate contact with the slag [14]. These weld pool reactions depend upon the kinetic considerations. In this study, CaF_2 , FeMn and NiO additions were made to the base fluxes $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3$ and their effects on the transfer of carbon, manganese, sulphur, phosphorus, nickel and silicon have been investigated. CaF_2 tends to reduce the weld metal oxygen content but this effect is supposed to be due to dilution of metal oxide rather than a direct chemical reaction [15]. CaF_2 improves de-sulphurizing and de-phosphorizing, and lowers the weld oxygen content [16]. FeMn and NiO additions increase Mn and Ni to the weld metal, which are supposed to improve the strength of the weld. The Mn and Ni promote formation of acicular ferrite, which is supposed to be good for mechanical properties [17]. Mild steel has good weldability with moderate strength, and it is the most widely used steel in fabrication and structural applications. Hence, the aim should be to improve the strength of welded structure and it should be safe against brittle fracture. In high-carbon steels the strength may be high but the chances of brittle fracture are also high. Hence, because of general, critical and versatile applications, mild steel was selected for this study.

2. Experimental procedure

To investigate the effects systematically, 20 fluxes were designed using response surface methodology (RSM). The design matrix in coded form is given in table 1. The fluxes were prepared by agglomeration technique. The base constituents CaO , SiO_2 and Al_2O_3 were mixed in the ratio 7:10:2 based on ternary phase diagrams. These base fluxes were selected as these are the most widely used commercial fluxes for low-carbon steel. The role of various ingredients in the flux is given as follows.

- CaO : it is a stable oxide and it helps in removal of sulphur and phosphorus from the weld metal. It also improves impact strength of the weld metal [18].
- SiO_2 : improves viscosity of the flux in molten state. It also improves current carrying capacity of flux in molten state. The bead appearance and slag detachability are also improved by the addition of SiO_2 . However, large amount of silica may result in poor mechanical properties.

Table 1. Design matrix in coded form.

No of experiment	CaF_2 (wt%)	FeMn (wt%)	NiO (wt%)
1	+1	-1	-1
2	0	+1	0
3	+1	-1	+1
4	-1	-1	-1
5	0	0	0
6	0	0	0
7	+1	+1	+1
8	0	0	0
9	0	-1	0
10	+1	0	0
11	0	0	+1
12	-1	-1	+1
13	0	0	0
14	0	0	0
15	+1	+1	-1
16	-1	0	0
17	0	0	0
18	0	0	-1
19	-1	+1	+1
20	-1	+1	-1

- Al_2O_3 : improves impact strength of the weld because it promotes the formation of acicular ferrite.

The additives CaF_2 , FeMn and NiO were selected as control parameters and were added in varying range (2–8%). These additives were added to the base constituents to know their effects on elements C, Mn, Ni, Si, S, P and O transferred to the welds. The percentage of the additives was based on the fact that the flux constituents melt 50–70°C prior to the melting of base plate. The three levels of the aforesaid additives are shown in table 2. The composition of base plate and wire is given in table 3 and the welding parameters such as voltage, current and travel speed, which were made constant during the welding process, are given in table 4. All the components, base constituents and additives were mixed in a container and potassium silicate was used as a binder for making these fluxes. The powder of CaCO_3 was used in place of CaO because of its hygroscopic nature. A photograph for preparation of the fluxes has been shown in figure 1a. After preparation, the fluxes were heated in a furnace up to 400°C for more than 6 h to remove any traces of moisture. Before making the weld the fluxes were again heated up to 100°C.

Table 2. Three factors and their levels.

Factors	Additives (%)	Lower level (-1)	Middle level (0)	High level (+1)
A	CaF_2	2	5	8
B	FeMn	2	5	8
C	NiO	2	5	8

Table 3. Wire and plate composition.

Composition	Carbon (%)	Silicon (%)	Manganese (%)	Sulphur (%)	Phosphorus (%)	Nickel (%)
Base plate	0.03	0.07	0.34	0.017	0.022	–
Wire	0.11	0.09	0.45	0.021	0.021	–

Table 4. Welding parameters.

Sl. no.	Voltage	Current	Travel speed
1	30 V	475 A	20 cm/min

Beads on plate welds using SAW were made on 18-mm-thick plates. Four beads were made for each sample. Some

beads on plate welds are shown in figure 1b. For making beads on plate welds, an automatic SAW machine was used. A photograph of the machine is given in figure 2a. The specifications of the machine are CPRA 800(S) ESAB India Limited. Other specifications are as follows:

- primary voltage 415 V, 3 phase 50 Hertz,
- open circuit voltage 25–55 V,

Figure 1. (a) Preparation of fluxes. (b) Beads on plate welds. **Figure 2.** (a) Submerged arc welding machine. (b) Extracted powder for chemical analysis.

c. DC welding 800 A, 100% duty cycle.

In this study 10% dilution from the base plate has been considered so that we can study the effects of flux composition on element transfer to the welds. After making beads, the powder was extracted from the top bead with the help of a drill machine for chemical analysis. The extracted powder is shown in figure 2b. This powder was used for wet chemical analysis. The chemical analysis was done in Spectro Analytical Lab, Okhla, New Delhi, India.

3. Results and discussion

The results of chemical analysis of the weld beads are summarized in table 5. The delta quantity of the element present in the weld was calculated and it was used to interpret the effect of the flux constituents on the elements transferred to the weld metal. Indacochea *et al* [19], Dallam *et al* [20] and Their [21] have used this delta quantity to study slag metal reactions in SAW. This was calculated from the following formula:

Table 5. Showing Δ quantity for elements transfer during SAW.

Flux no.	CaF ₂ (%)	FeMn (%)	NiO (%)	CaO (g)	SiO ₂ (g)	Al ₂ O ₃ (g)	Carbon (%)	Silicon (%)	Manganese (%)
1	8	2	2	486	695	139	0.03	0.1	0.17
2	5	8	5	453	647	130	0.03	0.12	0.37
3	8	2	8	453	647	130	0.04	0.1	0.23
4	2	2	2	519	742	148	0.04	0.1	0.17
5	5	5	5	470	671	134	0.04	0.1	0.35
6	5	5	5	470	671	134	0.08	0.02	0.31
7	8	8	8	420	600	120	0.04	0.1	0.38
8	5	5	5	470	671	134	0.08	0.02	0.34
9	5	2	5	486	695	139	0.03	0.14	0.34
10	8	5	5	453	647	130	0.04	0.11	0.42
11	5	5	8	453	647	130	0.04	0.10	0.15
12	2	2	8	486	695	139	0.03	0.10	0.57
13	5	5	5	470	671	134	0.07	0.03	0.38
14	5	5	5	470	671	134	0.07	0.03	0.39
15	8	8	2	453	647	130	0.04	0.10	0.24
16	2	5	5	486	695	139	0.04	0.14	0.25
17	5	5	5	470	671	134	0.03	0.10	0.50
18	5	5	2	486	695	139	0.04	0.10	0.29
19	2	8	8	453	647	130	0.04	0.10	0.33
20	2	8	2	486	695	139	0.04	0.10	0.33

Flux no.	Sulphur (%)	Phosphorus (%)	Nickel (%)	Element transfer of carbon ΔC	Transfer of Si ΔSi	Transfer of Ni ΔNi	Transfer of sulphur ΔS	Transfer of phosphorus ΔP	BI	ΔMn
1	0.014	0.020	0.177	-0.072	0.0156	0.177	-0.0057	-0.0011	0.839	-0.267
2	0.015	0.024	0.702	-0.072	0.0356	0.702	-0.0047	0.0029	0.847	-0.069
3	0.015	0.021	0.544	-0.062	0.0156	0.544	-0.0047	-0.0011	0.973	-0.209
4	0.014	0.020	0.374	-0.062	0.0156	0.374	-0.0057	-0.0011	0.710	-0.269
5	0.014	0.022	0.388	-0.062	0.0156	0.388	-0.0057	0.0009	0.840	-0.089
6	0.013	0.015	0.250	-0.022	-0.0644	0.25	-0.0067	-0.0061	0.840	-0.129
7	0.014	0.024	0.477	-0.062	0.0156	0.477	-0.0057	0.0029	1.000	-0.059
8	0.016	0.019	0.270	-0.044	-0.0644	0.270	-0.0037	-0.0021	0.840	-0.099
9	0.015	0.021	0.474	-0.072	0.0556	0.474	-0.0047	-0.0001	0.832	-0.099
10	0.015	0.020	0.744	-0.062	0.0256	0.744	-0.0047	-0.0011	0.910	-0.019
11	0.011	0.020	1.330	-0.062	0.0156	1.330	-0.0087	-0.0011	0.910	-0.289
12	0.011	0.024	0.440	-0.072	0.0156	0.440	-0.0087	0.0029	0.832	0.131
13	0.015	0.017	0.320	-0.032	-0.0544	0.320	-0.0047	-0.0041	0.84	-0.059
14	0.013	0.019	0.340	-0.032	-0.0544	0.340	-0.0067	-0.0021	0.84	-0.049
15	0.011	0.020	0.054	-0.062	0.0156	0.054	-0.0087	-0.0011	0.847	-0.199
16	0.014	0.020	0.344	-0.062	0.0556	0.344	-0.0057	-0.0011	0.773	-0.189
17	0.013	0.021	0.452	-0.072	0.0156	0.452	-0.0067	-0.0011	0.84	0.061
18	0.013	0.023	0.366	-0.062	0.0156	0.366	-0.0067	0.0019	0.773	-0.149
19	0.014	0.020	0.502	-0.062	0.0156	0.502	-0.0067	-0.0011	0.847	-0.109
20	0.013	0.024	0.288	-0.062	0.0156	0.288	-0.0067	0.029	0.714	-0.109

$$\Delta \text{Quantity} = \text{Analysed composition} - \text{Expected composition.}$$

The expected composition can be calculated from the following relation (1):

$$\frac{\text{dilution} \times \text{base plate composition} + (100 - \text{dilution}) \times \text{wire composition}}{100} \quad (1)$$

As carbon, silicon, manganese, nickel, sulphur and phosphorus contents decide the weld microstructure and mechanical properties, the delta quantities were calculated for all these elements.

3.1 Transfer of manganese

From the experimental results shown in table 5, it is found that ΔMn value is negative for most of the welds. Only welds numbered 12 and 17 show the positive value of ΔMn . The negative value of ΔMn quantity indicates that Mn content has been transferred from the weld metal to the slag. It may be attributed to the formation of manganese silicate inclusions, which are more soluble in slag in comparison to the weld metal [14]. Manganese content may also be lost due to evaporation. Manganese vapour dominates welding arc and a large amount may be lost [22]. Since manganese is present in filler wire as well as in base plate and also in the flux as ferro-manganese, both dilution and slag metal reactions play an important role in the manganese transfer [23]. Delta (Δ) Mn quantity is more negative in welds numbered 1, 3, 4, 15, 16 and 18. This may be because of high oxygen content in the welds, which might be due to either decomposition of oxides at high temperature or low amount of FeMn in the flux [15]. The FeMn adds more manganese to the weld metal, which can work as a deoxidizer. From this it can be interpreted that Mn content transfer also depends on the oxygen present in the weld. Loss of Mn content has been observed by many researchers with increase of oxygen in the weld [24–26]. The highest negative value of ΔMn quantity is observed for flux 11. This may be attributed to low FeMn content in the flux or low BI of the flux. For flux numbered 12 and 17, ΔMn content is positive, which may be because MnO has more solubility in the weld in comparison with the slag. From table 5, it can also be interpreted that as SiO_2 in the flux increases, ΔMn becomes more negative. This shows that SiO_2 may be a major source of oxygen in the welds numbered 1, 4, 16 and 18.

Welds numbered 2, 7, 9, 10, 19 and 20 have less negative ΔMn value, which indicates that higher amount of Mn proportion has been transferred to the weld metal from the flux. It may be because of lower oxygen content in the welds or higher FeMn in the flux. Flux numbered 5, 6, 8, 13 and 14 all have the same composition and the weld Mn is almost constant for them. They also show lower ΔMn value, which may

Figure 3. Effect of BI on weld Mn transfer.

be because of low oxygen in these welds. The weld manganese content increases with increase in BI of the flux as shown in figure 3. This has also been verified by Maheswari [27]. It can also be interpreted on the basis of the activity of CaO, which increases with increase in BI of the flux.

Weld numbered 4 shows that it has also high negative delta Mn value, which may also be due to high CaO, SiO_2 and Al_2O_3 . The weld oxygen may be high due to higher SiO_2 and Al_2O_3 [15]. It can also be because of low BI of the flux. The BI has a direct correlation with weld Mn transfer. The weld manganese content increases with increase in BI as shown in figure 3. It was also substantiated by Maheswari [27]. It can also be interpreted on the basis of the activity of CaO, which increases with increase in BI.

Weld Mn content depends on its concentration in the flux; however, proportions of Ca and Mg present in the flux also affect the Mn content transfer [28]. Weld numbered 7 has low negative ΔMn value as it contains low CaO, SiO_2 and Al_2O_3 . Welds numbered 5, 6, 8, 13 and 14 have ΔMn values that are between the values of weld numbered 4 and weld numbered 7. The maximum amount of Mn content is transferred to the weld in flux numbered 12; although it contains low value of FeMn, but because of higher CaO, more Mn may be transferred to the weld. The minimum Mn proportion is found in weld numbered 11, which may be due to micro-segregation of Mn at the grain boundary [29]. This weld also contains the highest amount of nickel, which may promote micro-segregation. It may also be due to lower CaO in the flux.

CaF_2 also affects the transfer of manganese to the weld. As we increase the CaF_2 in the flux, more Mn content may be transferred to the slag and weld Mn content may be reduced. It may also be because of evaporation of the manganese. This has been shown in figure 4. From figure 5 it can also be inferred that as NiO increases, the weld Mn content is also increased. This may be attributed to the increase in BI of the flux with increasing NiO additive. If

Figure 4. Effect of CaF_2 on weld Mn content.

Figure 6. Effect of basicity index on weld silicon content.

Figure 5. Effect of NiO on weld Mn content.

Mn^{2+} with SiO_4^{2-} ions, may also be important [32]. The BI does not show much significant effect on silicon transfer to the weld as shown in figure 6. It is slightly reduced with increasing BI. This may be attributed to the reaction of CaF_2 with SiO_2 to form SiF_4 [33]. This may also be because of very low variation in BI of the prepared fluxes. In this study, most of the fluxes led to little changes in silicon content of the welds except the fluxes numbered 6, 8, 13 and 14. It might be because the quantities of Al_2O_3 and SiO_2 do not vary very much in these fluxes. Al_2O_3 can replace the silicon in the SiO_2 network [28]. Silicon content in the weld may increase because of this replacement. This study also shows that Si content in the weld increases with increase in Al_2O_3 . This has been depicted in figure 7. However, this increase is very less as the changes in Al_2O_3 content of the fluxes are also not very significant. This also has been verified by Bang *et al* [34].

the basicity of the flux is more, the weld oxygen might be less and the weld Mn content may be increased.

3.2 Transfer of silicon

ΔSi value is found positive for most of the welds (table 5). It may be attributed to SiO_2 content, which is a major constituent of all the fluxes. The positive value shows that silicon has been transferred from the flux to the weld. This transfer may be explained on the basis of thermochemical disassociation of SiO_2 [30] and chemical reactions [31]. ΔSi value is negative for welds numbered 6, 8, 13 and 14, which shows that silicon is transferred from the weld to the slag in these fluxes. In these welds, as ΔMn value is less negative, it can be said that either they might have low oxygen content or thermal disassociation of SiO_2 may be low. Hence, the weld Si content may also be low, although other reactions such as formation of manganese silicate,

Figure 7. Effect of Al_2O_3 on weld silicon content.

3.3 Transfer of nickel

The transfer of nickel content has been found to be directly related to the amount of flux melted during the welding. In case of Ni, almost all the nickel content is transferred to the weld. In case of nickel transfer, slag-metal reactions will be the major factor as flux is the only source for nickel. Weld nickel increases directly with increase of NiO additions as shown in figure 8.

Weld numbered 11 is found to have the highest nickel content. It can be interpreted on the basis of high BI of the flux and higher content of NiO in flux 11. Slag-metal reactions play an important role in the transfer of nickel to the weld. The lowest nickel has been transferred in the weld numbered 15 and again it may be due to low amount of NiO content in the flux. Weld nickel content also increases with increase of BI of the flux (figure 9). It had also been verified by Maheswari [27].

Figure 8. Effect of NiO on nickel transfer to the weld.

Figure 9. Effect of BI on nickel transfer to the weld.

3.4 Transfer of carbon

The results of the weld metal composition given in table 5 shows that there is a loss of carbon content for all the welds. It indicates that carbon has been transferred from the welds to the slag in all the fluxes. The carbon content of all the welds ranges from 0.03% to 0.08%. The carbon content increases with increase of BI of the flux. This has been shown in figure 10. A probable reason may be the reduction in oxygen content with increasing BI. However, BI alone cannot be a true measure of oxidizing power of the flux. The BI of the flux may reduce the weld oxygen content and consequently, the carbon transfer to the slag may be reduced. It can also be seen from table 5 that less negative value of ΔC is found for those welds, which also have less negative value of ΔMn . From this it can be interpreted that weld oxygen present plays an important role in deciding the weld carbon. Welds numbered 6, 8, 13 and 14 have higher carbon content, which may be due to low oxygen in the weld as they have less negative value of ΔMn . Low carbon is mainly due to the oxidation of available oxygen in the weld. In these welds, high carbon content may also be attributed to low silicon content for the following reason: if the silicon content is in a particular range, it suppresses the formation of CO and less carbon may be removed from the weld [34, 35]. The reaction of carbon is given by the equation

As the flux basicity is not related to the weld carbon, it can be concluded that BI of the flux is not a true measure of oxidizing power of the flux. With increase of FeMn additive, carbon content of the weld also increases. This has been shown in figure 11. This might be because of reduction in oxygen content with increasing FeMn.

Figure 10. Effect of BI on weld carbon.

Figure 11. Effect of FeMn on weld carbon.

3.5 Transfer of sulphur and phosphorus

The chemical analysis given in table 5 shows that both sulphur and phosphorus are removed from almost all the welds. The sulphur content of the welds ranges from 0.011% to 0.015%. From the chemical analysis of the welds in table 5, it seems that the flux constituents that produce more oxygen in the welds do not help in desulphurization. Welds numbered 1, 3 and 4, which have higher ΔMn (higher oxygen), remove less sulphur. However, welds numbered 8, 9, 10 and 13, which contain less negative ΔMn (lower oxygen in the weld), also show low desulphurization. It may be due to low basicity of the flux. In this study, BI of the flux does not show significant effect on ΔS as shown in figure 12. This may also be due to very low variations in BI of the prepared fluxes. All the fluxes are acidic in nature and have BI less than one. Welds numbered 18, 19 and 20 may have low oxygen due to low negative ΔMn and show high desulphurization.

ΔP is positive for welds numbered 2, 5, 7, 12 and 18. For these welds, ΔMn is less negative except for weld numbered 18. From this it can be inferred that phosphorus

Figure 12. Effect of basicity index on ΔS .

removal is also affected by weld oxygen content. More phosphorus is removed from those welds that have higher negative ΔMn , as is evident from table 5.

3.6 Modelling and analysis of weld sulphur transfer

The ANOVA table (table 6) shows that interactions of AB , AC and BC are significant for the model. The model is significant and lack of fit is insignificant. The statistics of the model shows that Pred. R -squared and Adj. R -squared are in close agreement. The R -squared value of the model is 0.8438 and there are only 1.3% chances that this model may be insignificant. The model has been improved by inverse transformation and the model is further improved by backward reduction. The normal probability plot is a straight line as shown in figure 13. The predicted values are also close to the actual values.

The developed equation for weld sulphur is given by the equation

Table 6. ANOVA table for Sulphur Surface Reduced Cubic Model.

Analysis of variance table [partial sum of squares – type III]						
Source	Sum of squares	df	Mean square	<i>F</i> value	<i>p</i> -value <i>P</i> > <i>F</i>	Remark
Model	1131.63	10	113.16	4.861	0.013	Significant
<i>A</i> -CaF ₂	22.55	1	22.55	0.969	0.3507	
<i>B</i> -FeMn	10.52	1	10.52	0.452	0.5183	
<i>C</i> -NiO	97.80	1	97.80	4.201	0.0706	
<i>AB</i>	182.68	1	182.68	7.847	0.0207	Significant
<i>AC</i>	182.68	1	182.68	7.847	0.0207	Significant
<i>BC</i>	196.95	1	196.95	8.461	0.0173	Significant
<i>A</i> ²	19.27	1	19.27	0.828	0.3866	
<i>B</i> ²	69.53	1	69.53	2.987	0.118	
<i>C</i> ²	410.74	1	410.74	17.645	0.0023	
<i>A</i> ² <i>C</i>	109.56	1	109.56	4.707	0.0582	
Residual	209.51	9	23.28			
Lack of fit	17.84	4	4.46	0.116	0.9709	Not significant
Pure error	191.66	5	38.33			
Cor. total	1341.13	19				
Model statistics						
Std. dev.	4.82		<i>R</i> -squared		0.8438	
Mean	74.09		Adj. <i>R</i> -squared		0.6702	
C.V. (%)	6.51		Pred. <i>R</i> -squared		0.4864	
Press	688.82		Adeq. precision		7.2452

Figure 13. Normal probability plot.

$$\begin{aligned} \frac{1}{\text{sulphur}} = & 98.11 - 12.88\text{CaF}_2 + 6.033\text{FeMn} - 13.49\text{NiO} \\ & + 0.531\text{CaF}_2 \times \text{FeMn} + 2.53\text{CaF}_2 \times \text{NiO} \\ & - 0.551\text{FeMn} \times \text{NiO} + 1.24\text{CaF}_2^2 - 0.558\text{FeMn}^2 \\ & + 1.357\text{NiO}_2 - 0.307\text{CaF}_2^2 \times \text{NiO}. \end{aligned} \quad (3)$$

3.7 Combined effects of additives on sulphur content

Figure 14 depicts the combined effect of CaF_2 and FeMn contents on sulphur transfer. This shows that the weld sulphur is increased on increasing both the additives. This

Figure 14. Combined effect of CaF_2 and FeMn on sulphur content of the weld.

Figure 15. Combined effect of FeMn and NiO on sulphur content.

may be attributed to the reduction in weld oxygen content on increasing both the additives. The combined effect of FeMn and NiO has been depicted in figure 15. This shows that the weld sulphur transfer is reduced on increasing both FeMn and NiO. This again may be explained in correlation with the weld oxygen. NiO after decomposition may produce more oxygen as this is not a very stable oxide.

3.8 Effect of dilution on elements transfer during SAW

Figures 16–19 show the effect of dilution on Mn, Ni, Si and C contents transferred to the weld in SAW. The weld Mn content increases while the Ni content is reduced with increasing dilution of the welds; this has been depicted in figures 16 and 17, respectively. The increase of weld Mn content with dilution may be attributed to slag-metal reactions and dilution as both may play an important role. The Mn may be transferred to the weld from the base metal

Figure 16. Effect of dilution on Mn transfer.

Figure 17. Effect of dilution on Ni transfer.

Figure 18. Effect of dilution on weld Si transfer.

Figure 19. Effect of dilution on weld C transfer.

and wire electrode as well as from flux. This is in agreement with the results obtained by Kanjilal *et al* [23]. However, for nickel content transfer, only slag-metal reactions are important as it is present only in the flux. The Ni content may also be reduced due to high-dilution metal reactions and may be transferred to the slag. The carbon content increases while the Si transfer is reduced with increasing dilution as shown in figures 18 and 19. This may be because of low oxygen content in the weld as the oxygen content is reduced with increase of dilution. The dilution of various welds is given in table 7.

Table 7. Dilution of various welds.

Weld no.	1	2	3	4	5	6	7	8	9	10
Dilution	0.387	0.179	0.454	0.366	0.467	0.281	0.257	0.555	0.399	0.388
Weld no.	11	12	13	14	15	16	17	18	19	20
Dilution	0.251	0.351	0.473	0.411	0.388	0.396	0.482	0.405	0.454	0.566

4. Conclusions

1. BI of the flux has a direct correlation with Mn and Ni content of the weld. The manganese and nickel contents in the welds increase with increasing BI of the flux, while weld Mn is reduced with increasing CaF_2 . The weld Mn content also increases with increasing NiO.
2. BI of the flux only cannot be a true measure of oxidizing power of flux.
3. Weld Mn content not only depends on its concentration in the flux but also depends on CaO present in the flux, while SiO_2 content seems to be responsible for weld oxygen content as ΔMn increases with SiO_2 in the flux.
4. Weld Si increases slightly with increase in Al_2O_3 in the flux, but decreases with increase in BI of the flux.
5. Weld carbon content increases with increasing BI and FeMn.
6. Basicity of flux does not show much effect on desulphurization, but weld oxygen seems to be correlated with the desulphurization.
7. Less sulphur transfer is observed in those welds that have less negative ΔMn (low oxygen in the weld). This can be established from table 5. The weld sulphur is increased with increase of both FeMn and NiO additives, while it is reduced with increasing CaF_2 and NiO.
8. Phosphorus content removal is increased from the weld if negative ΔMn is large. From this it can be interpreted that weld oxygen helps in removal of phosphorus.
9. The weld Mn content and weld carbon proportion increase with dilution, while weld Ni and silicon contents decrease with dilution.

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