Title	Effect of Submerged Arc Welding Flux Chemical Composition on Weldment Performance(Materials, Metallurgy & Weldability)
Author(s)	Ushio, Masao; Zaghloul, Bahaa; Metwally, Wafaa et al.
Citation	Transactions of JWRI. 1995, 24(1), p. 45-53
Version Type	VoR
URL	https://doi.org/10.18910/12780
rights	
Note	

Effect of Submerged Arc Welding Flux Chemical Composition on Weldment Performance†

Masao USHIO *, Bahaa ZAGHLOUL**, Wafaa METWALLY**, Abdel-Monem EL BATAHGY**, and Morsy Amin MORSY***

Abstract

This work focused on studying the effect of chemical composition of submerged arc welding flux on weldment performance. Five formulations of Si02 - Ca0 - Mn0 flux were prepared using local raw materials. The performance of the formulated flux was evaluated and compared with two imported commercial fluxes. The welding conditions used were within the range recommended for the imported fluxes.

It was found that at these welding conditions, the locally produced flux resulted in higher arc stability, better slag detachability, reasonable penetration, and lower hydrogen content. Also, on using the same welding wire with both imported and locally produced fluxes, lower Si and Mn contents, lower non metallic inclusion, less solidification cracking, a predominantly primary ferrite microstructure and higher toughness of weld metal were obtained in the case of locally produced flux.

KEY WORDS: (S A Welding flux composition) (Bead appearance) (Diffusible hydrogen content) (Arc stability) (Element transfer) (Microstructure) (Mechanical properties)

1. Introduction

Welding fluxes are complex, usually containing ten or more elements added intentionally, in addition to the impurites. The task that welding fluxes have to do is also complex and it is not easy to understand how a flux works and in which way its constituents contribute to various aspects of its behaviour.

In fact, the choice of compounds, the exact formulation and manufacturing process to be adopted in the preparation of a flux depend upon many factors including both technical and economical considerations (1-4).

During the past few years there has been a considerable interest in welding fluxes. In Egypt, flux-shielded arc welding, especially submerged arc and shielded metal arc welding account for more than 70% of all welding carried out. This indicates the importance attaching to the local manufacture of these fluxes.

In this study , a submerged arc welding flux for welding both mild and 500 MPa high strength steel was designed and produced using local raw materials. The performance of the locally produced flux was examined and compared with two imported commercial fluxes in respect of the function of chemical composition.

2. Experimental

Based on the MnO-SiO_2-CaO ternary diagram, a composition having a melting point of 1300 ^{o}C was selected (50% SiO_2, 25 % CaO, and 25% MnO). The percentages of the other constituents were determined by previous work.

Five formulations of agglomerated submerged arc welding fluxes; C1 - C5 were prepared as shown in **Table 1** using local raw materials, except the white titania which was imported. The agglomeration technique was adopted since it is more economic $^{5)}$. The local raw materials used were fluorspar, magnesite, white feldspar, calcite, quartz, and manganese ore with chemical compositions shown in **Table 2.**

The different raw materials were crushed and ground to 200 mesh using a rod mill. The formulated flux was prepared by dry mixing the required different ingredients which were proportioned to a total weight of 1000 g. Then wet mixing was carried out by adding 30% potassium silicate solution as a binder in an industrial

---

† Received on July 21, 1995

* Professor
** CMRDI, Cairo, EGYPT
*** CMRDI, Cairo, EGYPT (Present Graduate Student, Osaka University)

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan.

Table 1 Chemical compositions of locally formulated flues (Wt%)

Raw Material	SiO_2	Al_2O_3	MgO	$CaCO_3$	MnO_2	TiO_2	CaF_2	K_2O	Fe_2O_3	S	P
Fluorspar	12.6	2.46	-	2.7	-	-	82	-	.35	.05	.05
Magnesite	-	4	80.24	4.68	-	-	-	-	-	.01	-
Feldspar	72.1	21.4	-	1.4	-	-	-	12.72	-	.02	-
Calcite	1.2	.6	4.64	93.32	-	-	-	-	-	.07	-
Quartz	98.2	-	.04	.02	-	-	-	-	-	.05	-
Manganese ore	1.18	-	-	-	83	-	-	-	3.85	.1	.1
White TiO_2	-	.81	-	-	-	95.85	-	-	.93	.02	-

Table 2 Chemical composition of raw materials used (Wt%)

Flux symbol	SiO_2	CaO	$CaCO_3$	MnO	CaF_2	MgO	TiO_2	Al_2O_3	Fe-Si	FeO
C1	38	-	20	20	4.5	2.5	4	4	5	2
C2	38	-	10	20	14.5	2.5	4	4	5	2
C3	38	-	15	20	9.5	2.5	4	4	5	2
C4	34	-	20	20	9.5	2.5	4	2	5	2
C5	34	20	-	20	10	2	4	2	5	2

food mixer. The mixing process was stopped after the granular mixture reached 1-2 mm diameter. After drying the moist flux at room temperature for 24 hours, it was sieved to sizes ranging from 12 to 48 mesh using a set of standard sieves on a vibratory shaker of the eccentric-base type. Then it was baked in an electrically heated oven at different temperatures (400-600 ^{o}C) for different times (1-5 h) [6,7]. A batch of 900 g of flux was produced at the end of each run. completed flux was packed in plastic bags.

For a basis of comparison, two commercially imported fluxes were also used in this study.

Weldability characteristics including arc stability, slag detachability, weld bead appearance and diffusible hydrogen content were examined using carbon steel plates with 370 MPa tensile strength as a base metal and 2 mm diameter wire; YSW41 (JIS Z3311).

Mechanical properties including tensile strength, hardness and impact value of the weld metals were evaluated using carbon steel plate; 17Mn4 (DIN 17155) as a base metal and 4 mm diameter wire; S3 (DIN 8557).

Weld metal analysis at both weld face and mid depth of the weld zone was carried out. Also, solidification cracking behaviour, element transfer and microstructure were investigated.

3. Results and Discussion

3.1. Evaluation of the Formulated Fluxes

The evaluation of the five locally produced fluxes was carried out by investigation of bead appearance, slag detachability, hydrogen content, and radiographic inspection as shown in Table 3.

Concerning C_1 flux, the flat-to-concave appearance of the weld bead could be related to the low surface tension between slag and weld metal. The observed surface depressions could be attributed to a relatively high viscosity of slag which in turn prevents gas escape. The entrapped gases press the surface of the weld metal resulting in pock marks and surface depressions.

Increasing CaF_2 to 15% and decreasing $CaCO_3$ to 10% (C_2 flux) resulted in a convex bead appearance having surface depression, sharp ripples and weld contour variation as shown in Fig. 1-a. However , slag detachability was improved due to the difference in thermal expansion coefficient between the slag and the weld metal. Also, weld metal diffusible hydrogen content was reduced as a result of increasing CaF_2 content. This could be attributed to dissociation of CaF_2 in the arc which in turn could result in suppression of hydrogen

Table 3 Results of weldability on using the five locally produced fluxes

Test	C1 flux	C2 flux	C3 flux	C4 flux	C5 flux
Bead appearance	- flat to concave - pock marks - surface depression	- flat to concave - sharp ripples	-pock marks	- smooth	- very smooth
Slag detachability	fair	good	good	good	good
Radiographic	good	good	good	good	good
Hydrogen content*	7	5	6	5.6	10

* JIS (ml/100g weld metal)

transfer due to the following reaction as has been reported by Mckeown[8] and Terashima [9]:

$$[H] + [F] \text{-----} HF \qquad (1)$$

On the other hand , reducing CaF_2 from15% to 10% and increasing $CaCO_3$ to15% (C_3 flux) led to a bead appearance having few pock marks which may be due to a relatively high viscosity of slag as in the case of C_1 flux. Weld metal diffusible hydrogen content was slightly greater than the C_2 flux but still lower than the C_1 flux.

In the case of C_4 flux, both SiO_2 and Al_2O_3 contents were slightly reduced in order to lower the slag viscosity. In this case , the weld metal diffusible hydrogen content was slightly decreased. However, the few observed surface depressions may be due to high amounts of gases resulting from decomposition of some raw materials especially $CaCO_3$.

In the fifth formulation (C5 flux) CaCO3 was decomposed before mixing, by backing at 1000 °C for 2 hours. In this case, bead appearance was very smooth having no defects (**Fig. 1-b**). This is due to decreasing the amount of CO_2 evolved from decomposition of $CaCO_3$. On the other hand, weld metal hydrogen content was significantly increased. This could be due to the formation of $Ca(OH)_2$ as a result of the reaction between CaO and water of the binder used. Formation of $Ca(OH)_2$ is detected by heat evolution , felt by hand touch, on adding the binder to the dry mixture during the agglomeration process.

3.1.1 Effect of CaO/CaCO3 ratio on bead appearance and hydrogen content

The above results showed that using CaO instead of CaCO3 resulted in improved flux performance. Therefore, it is speculated that the optimum performance of the flux will be affected by $CaO/CaCO_3$ ratio. This effect has been clarified using C_5 flux with four different $CaO/CaCO_3$ ratios (3:1, 1:1, 1:3, and 0:4) .

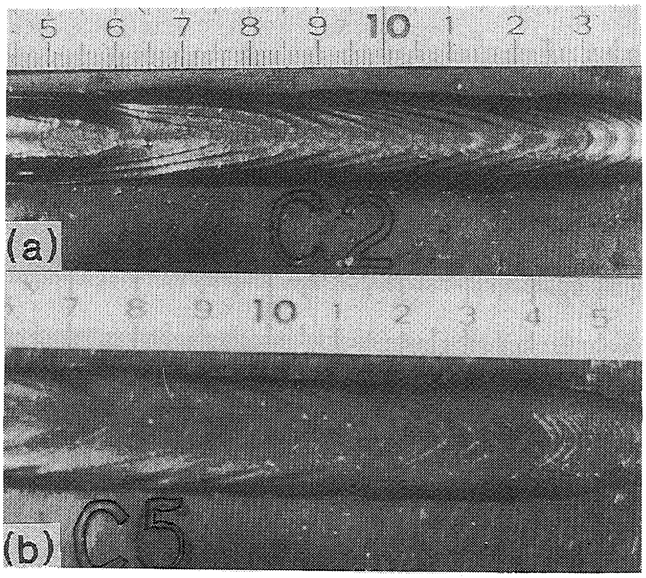

Fig.1 Weld bead appearance on using two locally formulated fluxes (a) C_2 flux (b) C_5 flux

Welding using $C_{5.1}$ flux ($CaO/CaCO_3$= 3:1) resulted in a smooth bead appearance . The internal surface of the slag produced was smooth and free from any gas pockets.

Using flux $C_{5.2}$ ($CaO/CaCO_3$ = 1:1) led to a smooth bead surface and the internal surface of the slag was also smooth and free fromgas pockets as shown in **Fig. 2-a.**

On the other hand, the high $CaCO_3$ content in $C_{5.3}$ flux ($CaO/CaCO_3$= 1:3) resulted in generation of large quantities of CO_2 gas that pressed the surface and led to pock marks. Flux $C_{5.4}$ resulted in a weld metal bead with a relatively large pock marks, compared with those obtained on using C5.3 flux (**Fig. 2-b**).

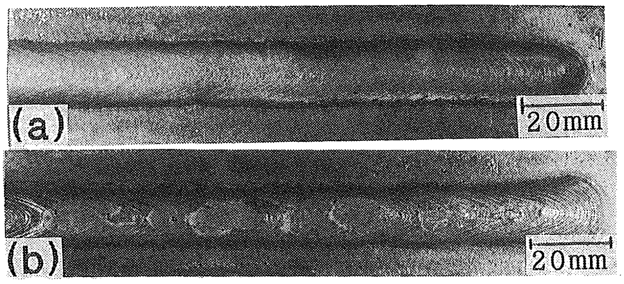

Fig.2 Effect of CaO/CaCO3 ratio on weld bead appearance
(a) $CaO/CaCO_3=1:1$ (b) $CaO/CaCO_3=0:4$

The effect of the $CaO/CaCO_3$ ratio on weld metal hydrogen content after baking the flux at 500 °C for different times is shown in **Fig. 3**. The weld metal diffusible hydrogen content increased with increasing $CaO/CaCO_3$ ratio. Increasing the baking time from 1 to 5 h resulted in a considerable decrease in weld metal diffusible hydrogen content. This could be attributed to the reduction of hydrogen partial pressure caused by generation of CO_2 during welding through the following reaction as has been pointed out by Terashima et al[10]:

$$CO_2 + H_2 \text{----------} CO + H_2O \qquad (2)$$

Based on the above results, it is clear that the formula of $C_{5.2}$ flux is characterised by a good bead appearance as well as a low hydrogen content. Weld metal hydrogen content of this flux as a function of baking temperature and time is shown in **Fig. 4** .The hydrogen content decreased with increasing baking temperature and/or time . However baking temperature is more effective in reducing hydrogen than baking time.

The performance of $C_{5.2}$ flux has been evaluated and compared with two commercially imported ones (A and B fluxes) . The chemical analysis of $C_{5.2}$, A, and B fluxes is given in **Table 4**.

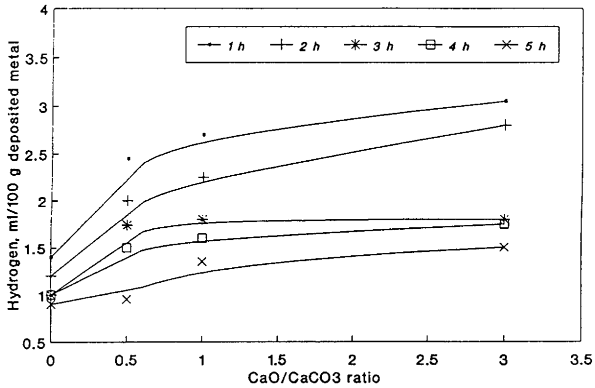

Fig.3 Effect of $CaO/CaCO_3$ ratio on diffusible hydrogen content of weld metal after baking the flux at 500 °C for different time

3.2. Comparison Between C5.2, A, and B Fluxes

3.2.1. Arc stability

Arc stability was first measured by the maximum fluctuation in arc voltage as it appeared on the voltage -meter on the control panel of welding machine. A more sensitive method was used to record the variation in reignition arc voltage with time. In this case, an accurate difference in average and reignition arc voltages was obtained using a high sensitivity adapter circuit connected with a recorder. The results obtained on using $C_{5.2}$. A, and B fluxes are shown in **Fig. 5 -a, b and c** respectively. The lower value of the reignition arc voltage obtained on using $C_{5.2}$ flux compared with that of A and B fluxes indicates a higher stability of the arc of this flux. This could be attributed to the higher Na_2O, K_2O, TiO_2, and CaO contents. Sodium, potassium, titanium, and calcium are characterised by low ionization potential that may provide a high conductive medium.

Table 4 Chemical compositions of locally produced ($C_{5.2}$), imported (A,B) fluxes (Wt%)

Flux symbol	SiO_2	MnO	CaO	FeO	CaF_2	Al_2O_3	MgO	TiO_2	K_2O	Na_2O
$C_{5.2}$	36.5	18.2	18.1	3	8.5	1.9	2.7	4.1	6.3	0.6
A	43	26	4.1	1.4	5	3	10.7	2	0.5	0.2
B	37.3	32.8	10.2	4.4	4	3.9	2.3	2.1	0.54	0.5

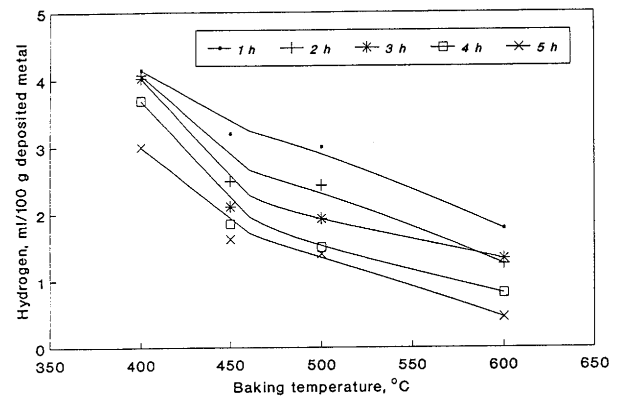

Fig.4 Effect of both baking temperature and baking time on diffusible hydrogen content of weld metal on using C5.2 flux

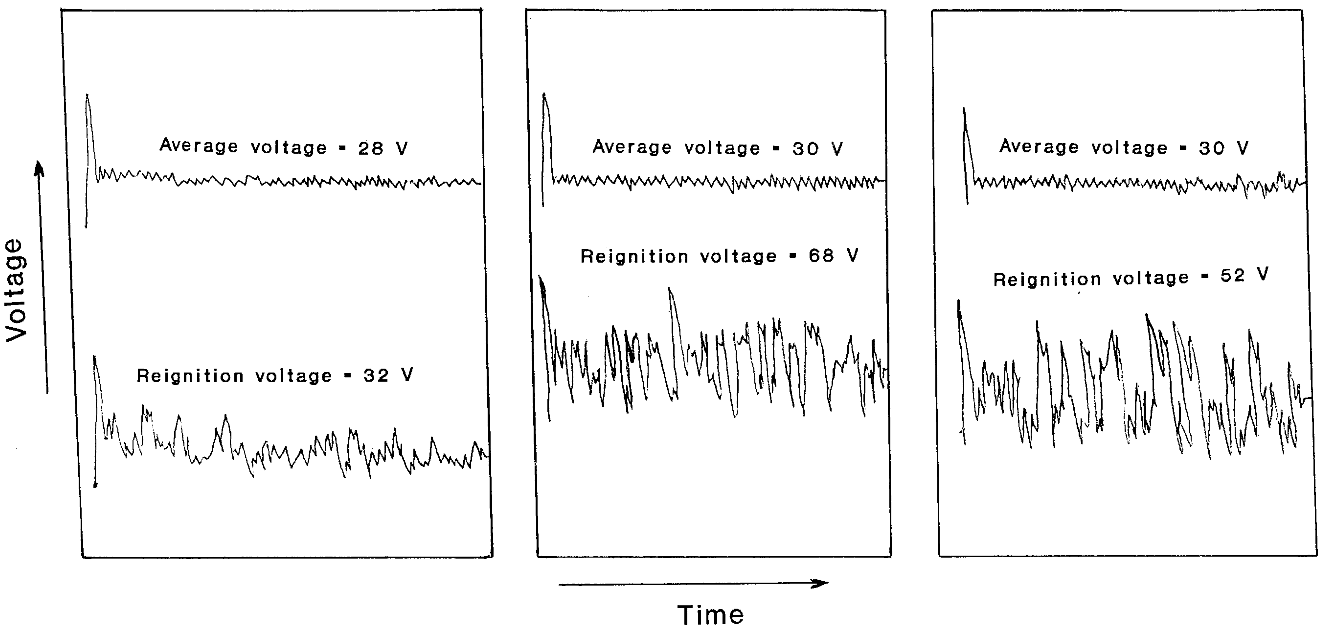

Fig.5 Comparison between arc stability on using $C_{5.2}$, A, and B fluxes

3.2.2 Weld bead appearance and hydrogen content

It was noticed that the bead surface appearance on using $C_{5.2}$ flux was smooth, free from undercut, pock marks or surface depression . Macrographs of cross sections of weld beads using $C_{5.2}$, A, and B fluxes are shown in **Fig. 6-a, b, and c** respectively. It can be noticed that the penetration obtained on using $C_{5.2}$ flux is nearly equal to those obtained on using the two imported fluxes. However, width/depth ratio of penetration (W/P) as well Width/ height (W/h) ratio were higher for $C_{5.2}$ flux than those of A or B fluxes. Reinforcement angle in the case of $C_{5.2}$ flux was larger than that obtained using the imported fluxes; A or B. This produces lower stresses at the toe and hence higher fatigue resistance which reflects a better performance of this flux in comparison with A and B fluxes.

Generally, bead shape depends on welding conditions such as current, voltage and travel speed as well as interfacial tension among base metal, molten slag and molten metal. Interfacial tension between base metal and molten metal is approximately constant for the same steel and heat input. However, interfacial tension between molten slag and both base metal and molten metal is a function of flux composition. Since welding conditions were kept constant for the three fluxes, weld bead shape can be directly related to flux chemical composition.

Regarding hydrogen content, $C_{5.2}$ flux baked at 600 ^{o}C for 1h has given 1.8 ml/ 100 g weld metal, whereas hydrogen contents due to using A and B fluxes were 2.3 and 2.8 ml/100 g weld metal respectively. This shows the superiority of $C_{5.2}$ flux resulting in extra low hydrogen content. For the same diffusible hydrogen content value of the three fluxes, it would be sufficient to bake $C_{5.2}$ flux at only 550 ^{o}C for 1 h .

3.2.3. Solidification cracking susceptibility

In this respect, A qualitative test was applied in which a 15 mm deep single V- groove with 45^{o} angle was prepared on 25.5 mm thick plate. A single bead was deposited in the single V-groove. Dye-penetrant tests showed that specimens welded using $C_{5.2}$, A, and B fluxes have surface cracks with lengths of 50, 56 and 30 mm respectively. However, radiographic inspection revealed that the accurate crack lengths were 270, 350, and 300 mm for the above specimens respectively.

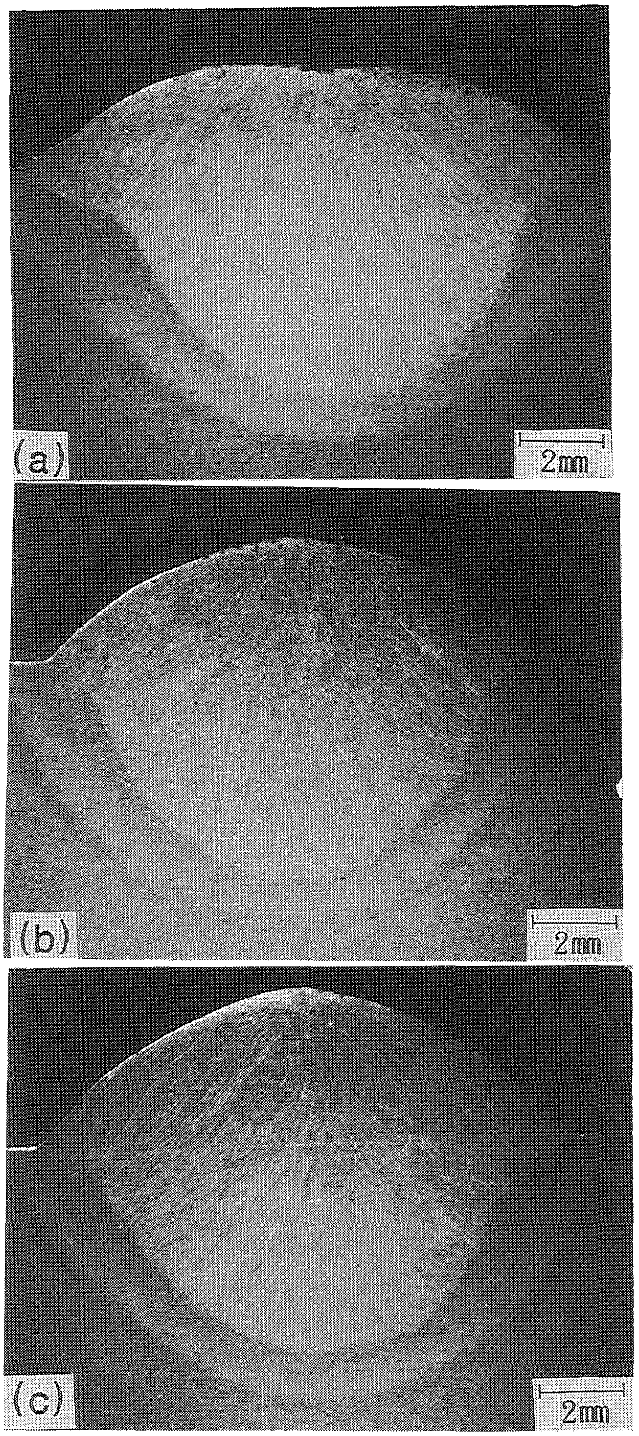

Fig.6 Macrographs of cross section taken from specimens welded using (a) $C_{5.2}$ flux, (b) A flux, (c) B flux

From these results, it can be noted that $C_{5.2}$ flux showed a lower solidification cracking susceptibility in comparison with A and B fluxes. This is due to a higher width/depth ratio for $C_{5.2}$ flux which permits the heat flow by conduction in all directions and helps to complete the solidification which in turn prevents cracking. On the other hand, a small width/depth ratio for A and B fluxes permits heat losses by radiation at the top of the bead . The heat loss by radiation at the top leads to closing of the top leaving a center line crack inside.

3.2.4 Element transfer

The chemical compositions of the top layer of all weld metals deposited using S3 and YSW 41 wires in combination with $C_{5.2}$, A, and B fluxes are shown in **Table 5.** Although SiO_2 contents of $C_{5.2}$ and B fluxes are equal , the weld metal silicon content on using $C_{5.2}$ flux was less than that of B flux. This could be attributed to the strong basic effect of CaO in the $C_{5.2}$ flux that renders part of silica metallurgically inactive through the following reactions:

$$CaO \text{ -------------- } Ca^{2+} + O^{2-} \quad (3)$$

$$SiO_2 + 2O^{-2} \text{ --------- } SiO^{4-} \quad (4)$$

Such consideration is supported by the data of Palm et al.$^{13)}$. Also, the presence of a considerable amount of CaF_2 in the $C_{5.2}$ flux reduces the oxidizing potential of SiO_2 and the subsequent Si content in the deposited metal through the following reaction as was reported by Tuliani et al.$^{11)}$:

$$2CaF_2 + SiO_2 \text{ --------} 2CaO + SiF_4 \quad (5)$$

The increase in sulphur content on using $C_{5.2}$ flux is due to the increase of sulphur content in the raw materials used in the manufacture of this flux. The increase of silicon content in the weld metal on using A flux could be related to an increase of flux silica content as has been pointed out by Heuschkel$^{12)}$. The increase in Mn content in weld metal on using A and B fluxes could be related to the higher MnO content of these fluxes in comparison with that of $C_{5.2}$ flux$^{13)}$.

It should be reported that the chemical compositions of the intermediate passes of all weld metals were almost similar to those of the top layer. This similarity of the chemical composition indicates the similarity of dilution at both top and intermediate passes.

3.2.5 Microstructure and mechanical properties

The microstructures of the top layers of multipass welds using C5.2 and A fluxes in combination with S3 wire are shown in **Fig. 7-a** and **b** respectively. It is clear that the microstructure obtained due to $C_{5.2}$ flux is predominantely polygonal ferrite compared with a bainitic structure in the case of using A flux. This could be attributed to the high Mn content (1.7%) in A flux $^{14)}$.

The microstructures of the middle parts of multipass welds using $C_{5.2}$ and A fluxes in combination with S3 wire are shown in **Fig. 8-a** and **b** respectively.

Table 5 Chemical compositions of top layer of weld metals (Wt%)

Flux	WW	C	Si	Mn	S	P
$C_{5.2}$	S3	0.09	0.289	1.11	0.027	0.016
	YSW 42	0.08	0.115	1.18	0.026	0.017
A	S3	0.075	0.736	1.73	0.017	0.016
	YSW41	0.07	0.49	1.61	0.018	0.016
B	S3	0.08	0.52	1.82	0.016	0.021
	YSW41	0.075	0.17	1.64	0.016	0.019

WW: Welding wire

It is clear that these microstructures are almost similar to those obtained for the top layer (Fig.7-a and b). This similarity of microstructure at both top and mid-pass layers indicates the similarity of mechanical properties of the joint at both top and mid-pass layers.

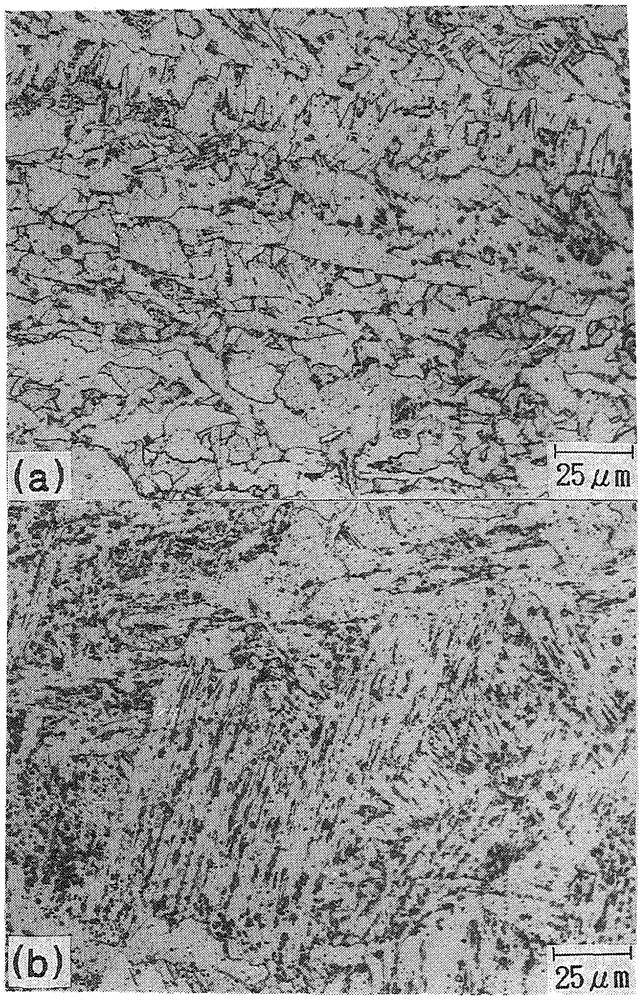

Fig.7 Optical photographs of weld top layer obtained due to using (a) C5.2 flux, (b) A flux

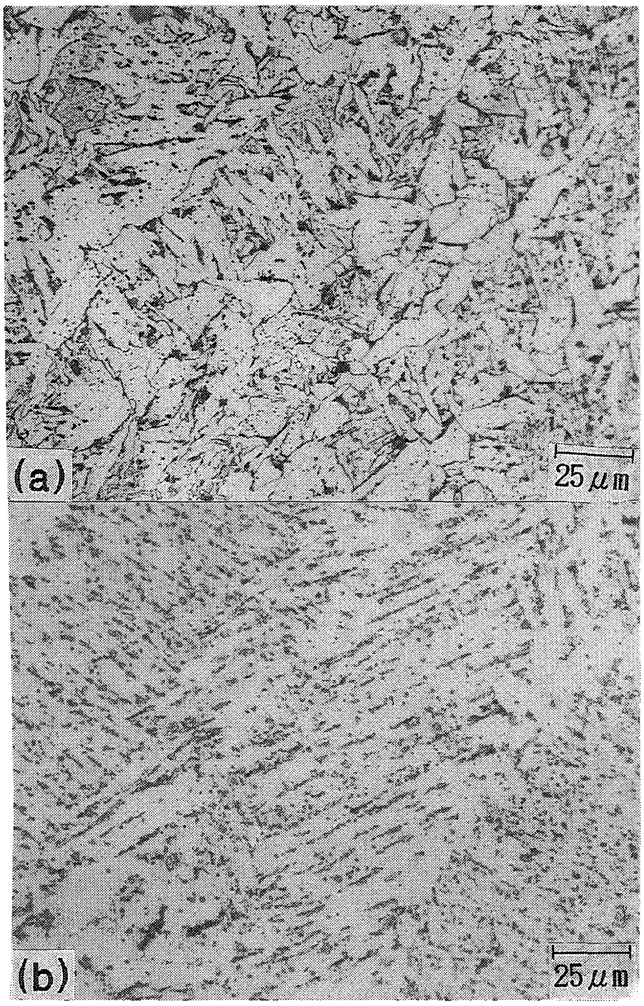

Fig.8 Optical photographs of weld intermediate layer obtained due to using (a) $C_{5.2}$ flux, (b) A flux

It should be reported that the microstructure obtained at both top and mid-pass layer due to using B flux was almost identical to that obtained due to using A flux.

Hardness measurments for the weld metal on using $C_{5.2}$, A, and B in combination with S3 wire has given an average values of 175, 187, and 180 Hv respectively.

The results obtained for tensile and impact tests of the weld metal when using $C_{5.2}$, A, and B fluxes in combination with S3 wire are shown in **Fig. 9**. It can be seen that tensile strength (T.S), yield stress(Y.S), and elongation values obtained on using $C_{5.2}$ flux were almost similar to those obtained on using both A and B fluxes. Another important observation is the high impact value obtained due to using $C_{5.2}$ flux in comparison with that obtained on using the two commercially imported fluxes ; A and B. This can be confirmed from observation of the fracture surfaces of the specimens welded using $C_{5.2}$ and A fluxes as shown in **Fig. 10-a** and **b** respectively . It is noteworthy that the ductile fracture mode dominant in the case of using $C_{5.2}$ flux (Fig. 10-a) is replaced by a brittle one using A flux (Fig. 10-b). It should be mentioned that the fracture surface of the impact specimen using B flux was almost the same as that obtained on using A flux. This could be related to the microstructure of the deposited metal which is predominantly polygonal ferrite in the case of C5.2 flux and bainite in the case of A and B fluxes. Polygonal ferrite structure is relatively soft and consequently the applied strain is uniformly distributed within the microstructure. These results are in good agreement with Dolby 15), Evans 16), and John et al18).

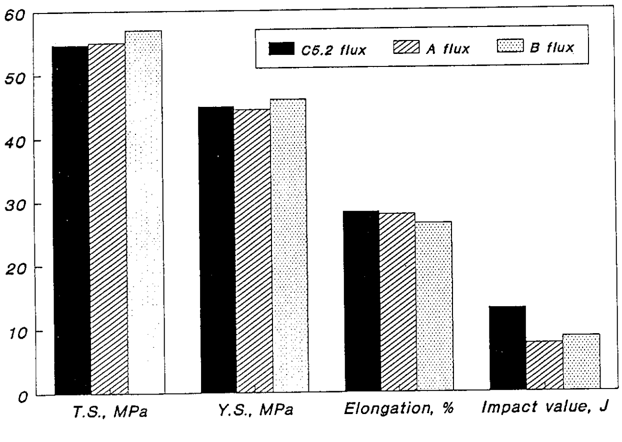

Fig.9 Comparison between tensile strength, yield stress, elongation and impact values obtained due to using $C_{5.2}$, A, and B fluxes

A qualitative estimation of non metallic inclusions showed that the lowest inclusion volume fraction in weld metal was obtained on using $C_{5.2}$ flux. This is also one of the reasons for the lower impact value of the weld metals using A and B fluxes as has been pointed out by Garland et al 19).

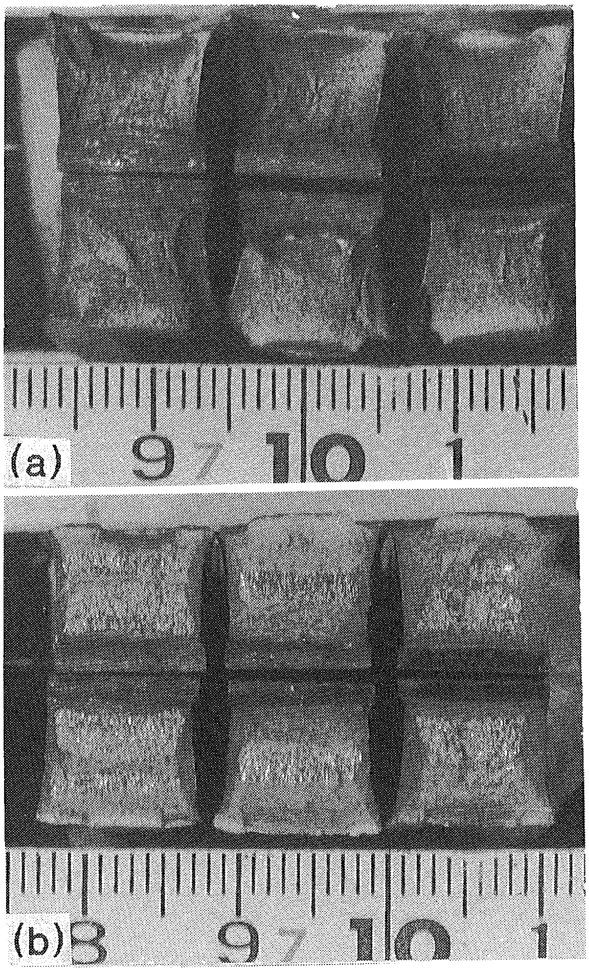

Fig.10 Macrographs of the fracture surface of impact tested specimens obtained due to using 9a) $C_{5.2}$ flux, (b) A flux

4. Coclusion

A MnO-SiO2-CaO flux was produced to investigate the effect of chemical composition of flux on the performance of the weldment. The following conclusion can be summarized:

(1) The performance of a submerged arc welding flux is related to its composition.

(2) CaF_2 has a beneficial effect on slag detachability and weld metal hydrogen content. However, higher CaF_2 content (15%) led to a convex bead appearance with surface depressions, sharp ripples and weld contour variations.

(3) $CaCO_3$ has a beneficial effect on weld metal hydrogen content while it has a harmful effect on bead appearance. High $CaCO_3$ content (20%) resulted to surface defects ranging from small pock marks to surface depressions.

(4) Partial dissociation of $CaCO_3$, with $CaO/CaCO_3$ ratio = 1, resulted in a low weld metal hydrogen content and good bead appearance with no defects.

(5) Wire/ flux combination is important in determining weld metal composition and consequently microstructure and mechanical properties of weld metal.

(6) In comparison with two imported commercial fluxes, locally formulated flux has a superior performance concerning arc stability, bead geometry, resistance to solidification cracking, and impact value at the used welding conditions.

Acknowledgement

The authors would like to express their great thanks to Dr. R. Kohno, Nippon Steel Corporation for his helpful assistance in accomplishing this work. The author are also greatly indepted to Mr. Ashraf Selim , Orlecon Co. Ltd. for welding consumables , Cairo, Egypt.

References

1) Jackson, C. E., Weld. Res. Council Bull., No. 190, December 1 973.
2) Bennett, A. P. , Metal Construction, 1969, (10), P. 455.
3) Bennett, A. P., and Stanley, P. J., Brit. Weld. J., 1966, (2), P. 59
4) Campbell, H.C., and Johnson, W. C., Welding Journal, 1957, 36(11), P. 1078.
5) W.T.T, Series -3, Welding Consumables, Kobe Steel, LTD, Welding division, 1987.
6) Belton, G. R., Moore, T. J., and Tankins, E. S., Welding Journal, 1963, 42(7), P. 290s.
7) Webb, W., Ph.D. Thesis , Cranfield, United Kingdom , 1969.
8) McKeown, D., Metal Construction, 1985, 17 (10) , P. 655.
9) Terashima, H., and Tsuboi, J., Metal Construction, 1982, 14(12),P.648.
10) Mallett, M. W., Welding Journal, 1946, 25(8), P. 396-S.
11) Tuliani, S. S., Boniszewski, T., and Eaton, N.F., Weld. and Metal Fabrication, 1969,(9), P. 327.
12) Heuschkel, J., Welding Journal, 1969, 48(8), P.328-s.
13) Palm, J. H., Welding Journal , 1972, 51(7), P.328-S
14) Kunitaki, T., Ohtani, H., Sumitomo Serch, 1969, 2(11), P. 18.
15) Dolby, R. E., Weld. Inst. Res. Report, Pt 2 ,14/1976/M, May 1976.
16) Evans, G.M., Welding Journal, 1982, 61(9), P.1 25-s.
17) Herrera, R., Timerman, R., and Gonzalez, J. C., IIW Doc., II-A, 1983, P. 598.
18). John, R., Kemp, P. R., and Welland, W.G., Metal Construction, 1976, 8(11), P.488.
19) Garland, J.G., and Kirkwood, P.R., Weld. and Metal Fabrication, 1976, (4), P.217.