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Influence of Heat input on Corrosion Resistance of Duplex Stainless Steel Cladding Using Flux Cored Arc Welding on Low Alloy Steel Flats

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ABSTRACT

Cladding is deposition of material on a corrosion-prone substrate to protect it from corrosion. Duplex stainless steel cladding is reported to have the ability to offer good corrosion resistance. In the present work, duplex stainless steel (E2209 T0-1) filler material is used for depositing a single layer with 50% overlap on E250 low alloy steel substrate using FCAW process with 100% CO_2 as shielding gas. Three sets of heat input are chosen for the experiment. Each set has different welding voltage and current, whereas travel speed has been kept constant for all experimental runs. Experiments have been replicated twice. 24-hour accelerated corrosion test is conducted on the clad surface in ferric chloride and hydrochloric acid solution. Results obtained from corrosion test indicate that all clad parts have better pitting corrosion resistance than the base metal. Corrosion resistance of clad parts exhibits decreasing tendency with greater heat input on the whole. Polynomial regression analysis is used to establish the quadratic relationship between heat input and pitting corrosion rate that indicate corrosion rate to increase with increase in heat input. ANOVA table depicts that the results obtained in pitting corrosion test against different heat input conditions are significant with high (95%) confidence level. The value of R^2 (0.7014) indicates fairly good association between heat input and corrosion rate.

Key words: cladding; FCAW; heat input; corrosion; regression analysis.

1.0 INTRODUCTION

In hostile environment, structural members are subjected to wear and corrosion, which degrades the surface causing weakening of the structure and affecting economy [1]. To tackle this, different types of surface treatment may be used. These can be metal spraying, plating, coating, cladding, etc. Among various surfacing techniques, cladding is widely used in industries as an economic engineering solution to protect a corrosion prone material against corrosion attack [2-3]. A number of welding processes are used for weld cladding. Flux cored arc welding (FCAW) is a well accepted method for weld cladding due to its high productivity and flexibility over many other processes [4-5]. Materials having corrosion resistance, erosion resistance, oxidation resistance, and fatigue resistance properties may be applied on the surface of other materials which are cheap, easily available but respond poorly in severe working conditions to increase service life of the later with better mechanical properties in a relatively cheaper way. Quality of the clad parts produced by welding can be improved by optimizing process parameters of that welding process [6-7]. Heat input plays an important role not only to produce better weld bead geometry [8], but also on corrosion resistance [9-14] and mechanical properties [15].

Among different stainless steels used as cladding materials, austenitic stainless steel provides good corrosion resistance property along with mechanical strength at relatively low price [16, 17]. Duplex stainless steel, on the other hand, is costlier but exhibits excellent corrosion resistance as well as better mechanical properties. Both austenite and ferrite phases are present in duplex stainless steel [18]. The presence of ferrite content is too important for obtaining good mechanical and corrosion resistance [19].

In the present work, investigation was carried out to explore the effect of heat input on hardness, microstructure and corrosion resistance characteristics of cladding with duplex stainless steel on E250 low alloy steel base material using gas metal arc welding process with a shielding gas of 100% CO_2 under varying process parameters. Three heat inputs are chosen for cladding. Process parameters like welding current and welding voltage are selected in three levels in such a way that it may produce the chosen heat input. Arc travel speed was kept constant during cladding experiment. Pitting corrosion test and metallography were performed to investigate the influence of heat input on pitting corrosion rate. Polynomial regression analysis is adopted to evaluate the quadratic relationship between heat input and corrosion rate corresponding to cladding.

2.0 EXPERIMENTAL PROCEDURE

Weld cladding was performed on ESAB India Ltd. made welding machine (Model No. Auto K 400), having 60% duty cycle. E250 low carbon structural steel plates of size 70mm x 60mm x 25mm were used as the substrate. Flux cored duplex stainless steel wire of 1.2 mm diameter, manufactured by ESAB, Sweden, was used as the electrode for cladding. The composition of base material E250 and Duplex stainless steel is shown in **Table 1** and **Table 2** respectively. Carbon equivalent, C_{eq} for the base material E 250 and electrode material E2209 T-01 are found to be nearly 0.2915 and 5.88 respectively.

Cladding is done by means of FCAW process with duplex stainless steel filler wire. It is used for depositing a single layer of stainless steel on the substrate with 50% overlap (**Fig.1**). The welding gun is mounted on a motor driven vehicle capable for speed variation and is driven on a straight guide rail. Welding gun angle is kept constant at an angle of 75° with the help of a fixture. Three different sets of heat input (0.49 kJ/mm, 0.56 kJ/m and 0.66 kJ/mm) were chosen for this experiment and each set has corresponding values of process parameters like welding voltage and welding current, whereas travel speed is kept constant. Equation (1) is used to find heat input. The heat input and other process parameters chosen are shown in **Table 3**.

$$Q = \frac{V \text{ x } 1 \text{ x } 60}{S \text{ x } 1000} \text{ x } \eta \qquad (1)$$

where, Q = Heat Input (kJ/mm), V = Voltage (V), I = Current (A), S = Torch Travel Speed (mm/min) and η = Efficiency (In this case, it is taken as 0.8).

2.1 Corrosion test

Cut samples are cleaned, polished and finally weighed by a digital weighing machine (Model: M K 100E, Petit Balance) with a capacity of 100gm and a least count of 0.001gm. Samples are coated by teflon tape, leaving only the clad face exposed. Each sample is immersed in ferric chloride solution (a mixture of 29gm ferric chloride, 24 ml HCl and 76ml distilled water) for 24 hour. After removing from the corrosive medium, test samples

Table 1 : Percentage composition of E250 grade low alloy steel base metal

C	Mn	Si	P	Ni	Mo	S
0.19	0.49	0.14	0.06	0.0253	0.037	0.03
Pb	**La**	**V**	**Ti**	**Nb**	**Cu**	**Co**
0.0104	0.0021	0.0024	0.0024	0.0096	0.0053	0.0059
B	**Zr**	**As**	**Sn**	**Fe**		
0.0012	0.0025	0.0662	0.0137	<98.88		

Table 2: Percentage composition of duplex stainless steel (E2209 T0-1) wire electrode

C	Mo	Mn	Si	N	S	P	Ni	Cr
0.020	2.91	1.01	0.76	0.125	0.0087	0.018	9.09	22.52

Table 3 : Heat input and other process parameters of cladding

Sl. No.	Heat Input (kJ/mm)	Torch Travel Speed (mm/min)	Welding Current (A)	Welding Voltage (V)
1	0.49	450	160	29
2	0.49	450	170	27
3	0.49	450	190	24
4	0.56	450	180	30
5	0.56	450	200	27
6	0.56	450	210	25
7	0.66	450	200	31
8	0.66	450	210	29
9	0.66	450	220	28

are cleaned with water, dried and then weighed again. The weight loss by the corrosive medium is found by the difference of initial and final weight of the test samples. Corrosion rate is found by using equation (2). This test is a modified process of the standard ASTM G48 pitting corrosion test method.

$$\text{Pitting Corrosion Rate, } P = \frac{W}{A \times T} \text{ (in gm/m}^2\text{hr)} \quad (2)$$

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2.2 Observation of microstructure

Test samples are cut to 10mm x 10mm x 25mm in size from the clad workpiece. These samples are ground and polished. The samples are etched by combination of Waterless Kalling's reagent (100ml ethanol, 100ml HCl and 5gm $CuCl_2$) and Ralph's reagent (100cc water, 200cc Methyl Alcohol, 100cc HCl, 5cc HNO_3, 2gr $CuCl_2$, 7gr $FeCl_2$). These samples are observed under metallurgical microscope (Make: Metzer, India) at 200x magnification.

3.0 RESULTS AND DISCUSSION

Corrosion rate of base material comes out to be 428.68 gm/m^{2}hr. **Table 4** shows the results of corrosion test obtained from the duplex stainless steel clad test samples of two replications.

Table 4 : Results of pitting corrosion test of duplex stainless steel clad samples obtained from two replications

Sl. No.	1st Replications (Test Duration : 24 hr)				2nd Replications (Test Duration : 24 hr)			Average Pitting Corrosion Rate (gm/m^{2}hr)
	Heat input (kJ/mm)	Exposed Area (mm^2)	Weight Loss (gm)	Pitting Corrosion Rate (gm/m^{2}hr)	Exposed Area (mm^2)	Weight Loss (gm)	Pitting Corrosion Rate (gm/m^{2}hr)	
1	0.49	9.5×10.8	0.580	235.54	10×10.2	0.491	200.57	218.05
2	0.49	9.1×10.1	0.456	206.72	9.2×9.1	0.381	189.62	198.17
3	0.49	10.5×10.5	0.389	147.01	10.1×10.5	0.486	190.94	168.98
4	0.56	10×10.5	0.467	185.31	10.1×9.3	0.473	209.81	197.56
5	0.56	9.9×10.1	0.421	175.38	9.9×10.1	0.418	174.18	174.78
6	0.56	10.9×10.9	0.491	172.19	10.9×10.3	0.458	169.97	171.08
7	0.66	10.9×10.9	1.193	418.38	10.5×10.7	0.965	357.88	388.13
8	0.66	10×10	0.718	299.16	10.1×10.5	0.595	233.77	266.47
9	0.66	10×10.5	0.611	242.46	10.1×10.7	0.633	244.05	243.25

There is substantial decrease in pitting corrosion rate of duplex stainless steel clad piece than the base plate E250 as seen in **Table 4**. This is likely to be due to cladding with duplex stainless steel having rich content of chromium, nickel and molybdenum that improve corrosion resistance in chloride environment. The least corrosion rate is found at the lowest heat input of 0.49 kJ/mm with 24 V weld voltage and 190 A weld current. These tabulated results are plotted in **Fig. 1** to observe the changes in corrosion rate with heat input.

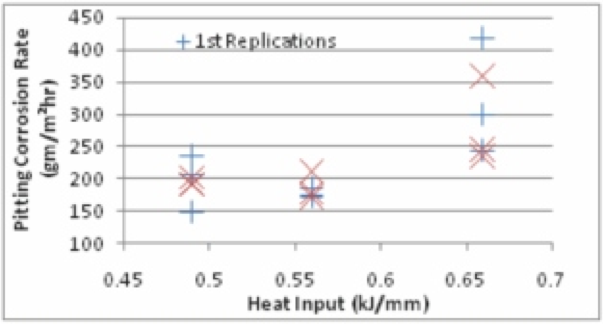

Fig 1 : Plot of pitting corrosion rate with heat input of duplex stainless steel clad piece obtained in two replications

Fig. 1 shows that with increasing heat input, pitting corrosion rate also increases. It is observed that at a high heat input of 0.66 kJ/mm, maximum pitting corrosion rate is found. At the intermediate heat input of 0.56 kJ/mm, lowest average pitting corrosion rate is found in this work. At a low heat input of 0.49 kJ/mm, low pitting corrosion rate is found. The graph clearly indicates that at the highest heat input of this experiment, i.e., 0.66 kJ/mm is showing poor corrosion resistance. Heat input of 0.49 kJ/mm and 0.56 kJ/mm are the best for cladding purpose to prevent corrosion. At a heat input of 0.49 kJ/mm with 24 V weld voltage, 190 A weld current and at a heat input of 0.66 kJ/mm with 27 V weld voltage, 200 A weld current and with 25 V weld voltage, 210 A weld current has the quite low pitting corrosion rate.

The corrosion rate found at base plate E250 is about 2.5 times the least corrosion rate found in the duplex stainless steel cladded test sample, and 1.9 times the average corrosion rate of duplex stainless steel cladded test samples.

3.1 Microstructure of cladding

Observation of microstructure of the clad portion is made under a metallurgical microscope. The Ralph's reagent and Waterless Kalling's reagent are used as etchant. The magnification is taken as 200X.

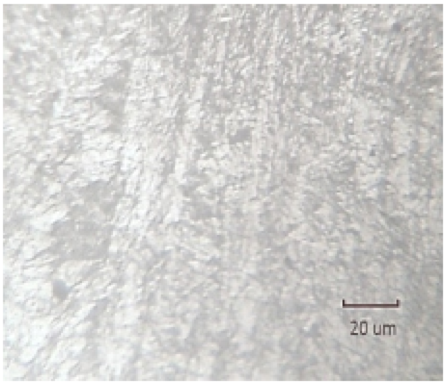

Fig 2: Test specimen 1

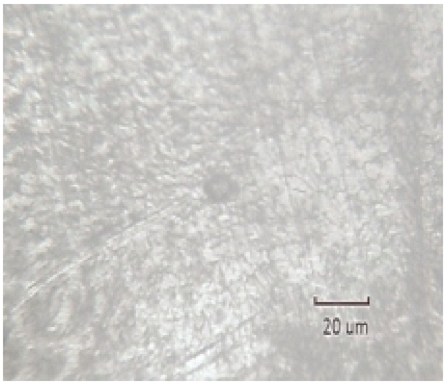

Fig 3: Test specimen 2

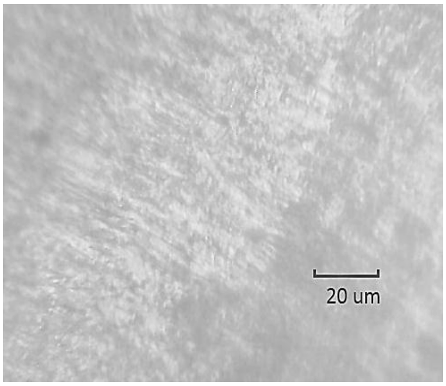

Fig 4: Test specimen 3

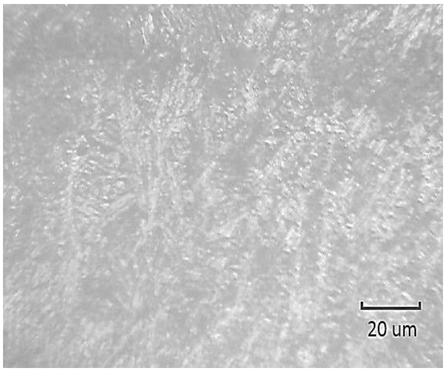

Fig 5: Test specimen 4

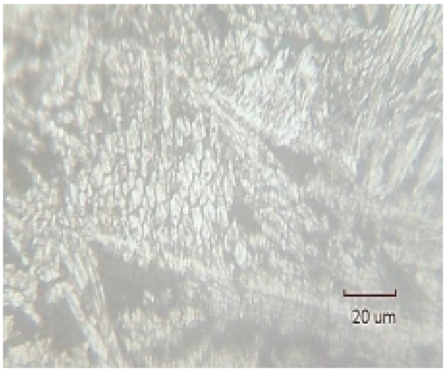

Fig 6: Test specimen 5

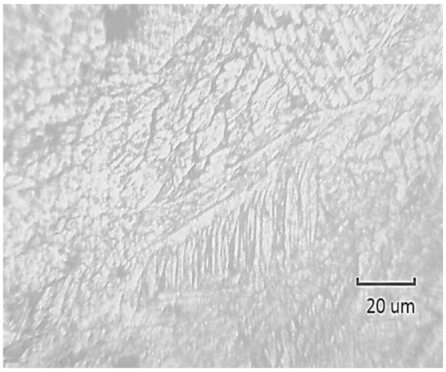

Fig 7: Test specimen 6

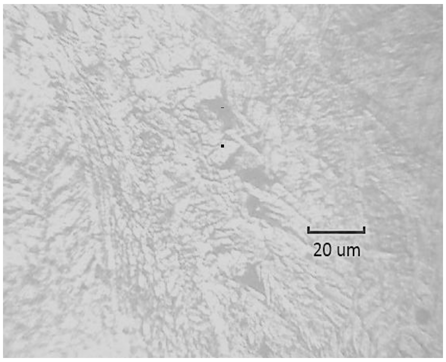

Fig 8: Test specimen 7

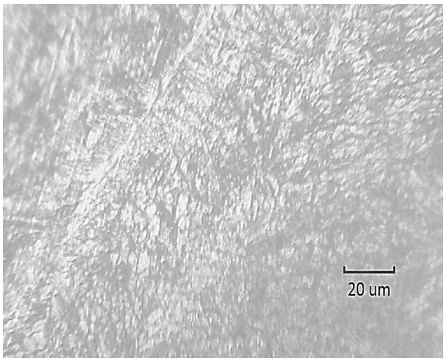

Fig 9: Test specimen 8

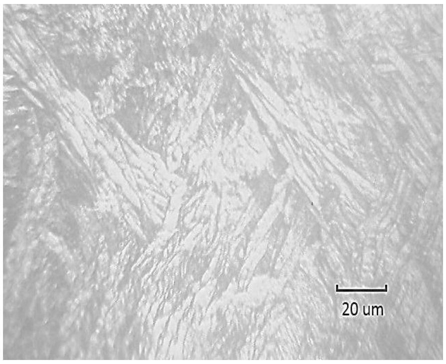

Fig 10: Test specimen 9

Fig.2 through **Fig.10** show microstructures of test samples, which broadly exhibit two common phases, i.e. austenite and ferrite. The blackish austenite phase is observed in white coloured ferrite matrix. The austenite and ferrite boundary are well defined in the microstructure. Elmer et al. [18] demonstrated that high Cr–Ni ratio alloys solidify with ferrite as primary phase. With decreasing cooling rate, more time is available for austenite precipitation from ferrite provided the final microstructure of single phase ferrite with secondary phase austenite (FA).

High rate of corrosion occurred at higher heat input condition that may be explained by the presence of lower amount ferrite at higher heat input, as can be seen from the typical microstructure of the clad zone.

Fig.11 shows photographs of corroded surface of sample no. 7 (mostly corroded) after corrosion test of duplex stainless steel clad test samples (two views). Both views show growth of corrosion pits.

3.2 Regression analysis

Polynomial regression analysis is done to evaluate the relationship between heat input and corrosion rate of clad sample. It provides 2nd order polynomial equation with high

Sample No. 7

Fig 11: Typical macrostructure of corroded surface of cladded zone after corrosion test of duplex stainless steel clad test at different zones value of R2 (71% approx.) and results obtained through regression equation agree with the experimental values with less error. ANOVA table (**Table 12**) suggests that the variation of results is significant at high level of significance (95%). **Fig.12** shows relationship between heat input and corrosion

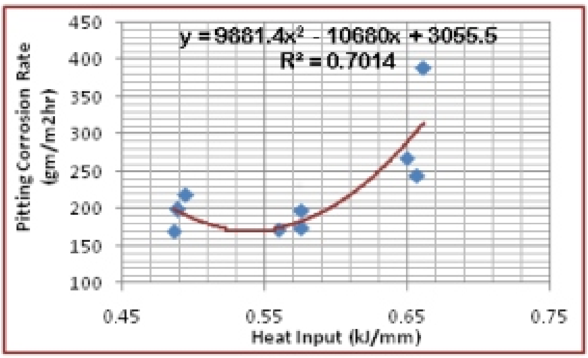

Fig. 12 : plot of pitting corrosion rate against heat input

Table 5 : The ANOVA table

Source	DF	SS	MS	F	P
Regression	2	27224.5	13612.2	7.05	0.027
Error	6	11589.1	1931.5		
Total	8	38813.5			

The relation between heat input and corrosion rate, P is shown in equation (3).

$$P = 3056 - 10680*Q + 9881*Q^2 \qquad (3)$$

where P and Q are corrosion rate and heat input respectively.

4.0 CONCLUSIONS

Experimental results of duplex stainless steel cladding highlight remarkable higher corrosion resistance than that of E250 low alloy steel base metal under chloride environment. Following are the conciousness that may be drawn from the present work :

a) Results of corrosion test clearly indicate that increasing heat input increases corrosion rate. At higher heat input, solidification time is more as solid state transformation causes more austenitic precipitation from single phase ferrite that may have increased corrosion rate. Least corrosion rate is found at the lowest heat input, i.e. 0.49 kJ/mm, with 24 V weld voltage and 190 A weld current in this work. At high heat input of 0.66 kJ/mm, maximum corrosion rate is found. Results also indicate that increasing welding current at the same level of heat input decreases corrosion rate.

b) Microstructural study of duplex stainless steel shows the microstructure of primary ferrite. Corrosion rate of E250 base plate is found to be more than 2.5 times the least corrosion rate found in the duplex stainless steel cladding.

c) Polynomial regression analysis suggests 2nd degree polynomial relation between heat input and pitting corrosion rate and moderately high value of R2 within experimental domain. The relationship is significant at a high level of significance as stated by ANOVA table.

d) Considering maximum corrosion resistance, heat input of 0.492kJ/mm with weld current of 140A and weld voltage of 28V seems the best condition within the domain of this investigation, and hence, may be recommended.

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