Effect of Heat Input on Intergranular Corrosion Resistance of Duplex Stainless Steel Clad Metals

T. Kannan[*1], N. Murugan[2] , I. Anbarasan[3]

[1] Principal, SVS college of Engineering, Coimbatore – 642 109, Tamil Nadu, India
[2] Professor of Mechanical Engineering, Coimbatore Institute of Technology, Coimbatore – 641 014, Tamil Nadu, India
[3] Assistant Professor of Mechanical Engineering, SVS college of Engineering, Coimbatore- 642 109, Tamil Nadu, India
[*] Corresponding Author E-mail : kannan_kct@yahoo.com

ABSTRACT

Cladding is a process of depositing a thick layer of a metal surface to a carbon steel or low alloy steel base metal for the purpose of providing a corrosion-resistant surface when that surface is to be exposed to a corrosive environment. Clad metals are more prone to corrosion attacks as compared to base metals because they are compositionally and microstructurally inhomogeneous. Claddings require a proper evaluation of their corrosion resistance in order to ensure that they are suitable for the desired applications. This paper focuses on an experimental study of duplex stainless steel cladding of low carbon structural steel deposited by flux cored arc welding process. In this research work, double-loop electrochemical potentiokinetic reactivation technique was employed to evaluate the intergranular corrosion resistance of the claddings. The effect of heat input on intergranular corrosion resistance is presented in graphical forms, which are very useful to control the corrosion resistance of the claddings.

Key words: Duplex stainless steel; Cladding; Flux cored arc welding; Intergranular corrosion resistance; Heat input.

1.0 INTRODUCTION

Weld cladding is an excellent way to impart corrosion resistance properties to the surface of a base metal, to conserve expensive or difficult-to-obtain materials by using a relatively thin surface layer on a less expensive base material. Typical metal components that are weld-cladded include the internal surfaces of carbon and low-alloy steel pressure vessels used in chemical, fertilizer, food processing and petrochemical plants, paper digester, urea and nuclear reactor vessels, etc.

The clad layer is generally obtained by using rolling, explosive welding and fusion welding processes. Among all those processes fusion welding is readily accepted by the industries due to its easy and versatile application and no legal implication of noise and safety [1]. Various fusion welding processes employed for cladding are shielded metal arc welding, submerged arc welding, gas tungsten arc welding, plasma arc welding, gas metal arc welding, flux cored arc welding, electroslag welding, oxy-acetylene welding and explosive welding [2]. Among the processes employed for weld cladding, flux cored arc welding is becoming increasingly popular and is readily accepted by the industries due to the following features [3] :

- High deposition rate and increased productivity
- Smooth welding characteristics and weld finish
- Lower cost for the shielding gas
- Simple and more cost effective post weld cleaning
- Reliable and consistent high quality weld metal deposit
- Low spatter and has all-positional capability
- Excellent weld appearance

Materials chosen for cladding applications are expected to remain with the designed strength and corrosion resistance throughout their life. However, being thermodynamically unstable, materials react with the environment and depending on the corrosiveness of the environment they either corrode severely or corrode at a very low rate with the formation of a passive film [4]. The destruction of this passive film either uniformly or at a localized spot leads to further corrosion and ultimately the materials fail to perform the intended service with the expected strength and corrosion resistance. Hence, the probability of breakdown of the passive film leading to "localized corrosion", namely, pitting corrosion, crevice corrosion, stress corrosion cracking, intergranular corrosion (IGC) and corrosion fatigue, has a significant role to play in the service life of cladded components.

In general, clad metals are more prone to corrosion attacks as compared to base metals because they are compositionally and microstructurally inhomogeneous. Moreover, welding defects such as porosities, inclusions, etc. strongly influence the corrosion behaviour of the claddings.

Corrosion that occurs along the grain boundaries of a metal or alloy is called intergranular corrosion [5]. Intergranular corrosion usually occurs due to the difference of potential between the atoms at the boundaries (anode) and those at grain center when a phase precipitates at the grain boundaries. When this situation exists and if the alloy encounters a corrosive medium, corrosion begins at the surface in the grain boundary region and then penetrates into the body of the alloy following the boundaries. Intergranular corrosion causes serious damage and is detrimental to the strength of the alloy.

Duplex stainless steels are well known for their good mechanical properties due to the presence of the two phases, ferrite and austenite. They also have a high resistance to intergranular corrosion. Nevertheless, the precipitation of intermetallic compounds at grain boundaries affects this resistance. Chromium and carbon content present in the stainless steel combine together to form a continuous network along the grains boundaries when cooled / heated slowly between 540° C and 850° C, thus depleting the adjacent areas from chromium, which results in reduced corrosion resistance of these areas when exposed to a corrosive medium [6]. Stainless steel claddings require a proper evaluation of their corrosion properties in order to ensure that they are suitable for the desired application.

The ASTM recommended practices for detecting the susceptibility to intergranular corrosion have three major deficiencies, namely: (1) they do not readily quantify the degree of sensitization (2) they are not rapid (with the exception of ASTM A262 practice A) and (3) they are destructive (with the exception of ASTM A262 practice A) [7]. The electrochemical potentiokinetic reactivation (EPR) technique is a quantitative, non-destructive, rapid method for detecting sensitization and is essentially suitable for use in site conditions. The EPR technique is also an important tool from a research viewpoint.

Two versions of EPR technique are practiced today i.e., the single and the double-loop reactivation methods. In the single-loop method, potential is scanned from the passive state, and any reactivation charge occurring during this process is taken as a measure of the degree of sensitization (DOS). In the double-loop reactivation method, the reactivation scan from the potential in the passive state is preceded by a scan (anodic polarization) from the open circuit potential. To measure sensitization, a ratio (I_r/I_a) is used in which I_a and I_r are the peak currents during forward and reverse scans, respectively. The proponents of the double-loop reactivation method claim certain advantages over the single-loop method. First, because the reactivation ratio represents sensitization of the material in double-loop method, it may automatically compensate for the changes in the alloy composition. However, it has not been shown that two alloys (differing in chemical composition) with same DOS give the same reactivation ratio in a double-loop test. Second, it is not necessary to polish the test surface to a very fine diamond finish, as in the case of the single-loop method. This advantage is particularly beneficial from the field use viewpoint.

The double-loop reactivation test was originally devised by Akashi et al. for the measurement of sensitization in austenitic stainless steels [8]. It has been shown to be more sensitive than the single-loop reactivation test because the results obtained are independent of both the inclusion content of the material and its surface finish [9]. The double-loop test utilizes a solution of 0.5 M H_2SO_4 containing 0.01 M KSCN as an activator in which the specimen is immersed and allowed to establish its free-corrosion potential. The potential of the specimen is then increased at a constant rate, taking the specimen through the active region and into the passive range, and then it is reactivated by decreasing the potential at the same rate. The corrosion current is continuously monitored during this sequence, and the degree of sensitization is assessed from the ratio I_r to I_a. To date, the technique has largely been applied to austenitic stainless steel.

Majdi and Streicher employed the double-loop reactivation method for detecting sensitization in AISI 304 stainless steels [10]. They concluded that the reproducibility of the double-loop test was excellent when optimum test conditions were maintained. Scully and Kelly conducted EPR method to evaluate the IGC susceptibility of a duplex stainless steel [11]. The results of the double-loop EPR test correlated well with metallographic examination using a modified electrolytic oxalic acid procedure similar to that described by ASTM standard

A262, practice A. The successful use of those procedures had not been previously demonstrated.

Muraleedharan et al. correlated the DOS measured by the EPR test and ASTM A262 practice E test for AISI 304 and 316 stainless steel [7]. They concluded that the degree of sensitization determined from ASTM A262 and double-loop EPR correlated closely. Nathalie Lopez et al. performed double-loop EPR tests on an austenitic stainless steel AISI 317L and a duplex stainless steel UNS S31803 in a solution containing 0.01 M KSCN + 2 M H_2SO_4 + 0.5 M NaCl [12]. They reported that the solution used for the double-loop EPR test was too aggressive for austenite stainless steel. Garz et al. evaluated susceptibility of the duplex stainless steel to intergranular attack using double-loop EPR test [13]. They used thioacetamid instead of KSCN as activator.

Moran and Lee studied the relationship between the microstructure and corrosion behaviour of the duplex stainless steel [14]. For this study, 2205 duplex stainless steel samples were solution heat treated at 1150° C followed by either cooling at various rates to 820° C and then water quenching to room temperature, or quenching to room temperature and annealing at 840° C for various lengths of time. A double-loop EPR test was carried out to examine the effect of various cooling procedures or annealing treatment on the sensitization of duplex stainless steel. Duret-Thual et al. employed EPR method for detecting the sensitization of 22 and 25% Cr duplex stainless steels [15]. They used sulphuric and hydrochloric acid mixtures as testing media. Among the electrochemical parameters investigated, the importance of the initial cathodic polarization was particularly pointed out as well as the quality of surface preparation.

Sun et al. studied the effect of dual-torch technique on the microstructural changes and corrosion properties of duplex stainless steel welds [16]. It was found that the corrosion rate increased with increasing torch pitch and/or decreasing GTA welding current. Amadou et al. carried out double-loop EPR test optimization in checking of duplex stainless steel intergranular corrosion susceptibility [17]. They used an electrolyte of 33 % H_2SO_4 solution with 0.3 % HCl, at room temperature and at a potential scan rate dE / dt of about 2.5 mVs-1, was chosen to evaluate the sensitization of duplex stainless steels. The interactions between precipitation, and IGC sensitization during duplex stainless steel aging were clearly shown by superimposing the time-temperature-start of precipitation and time-temperature-sensitization diagrams obtained from the tests performed for various levels of sensitization.

Barnhouse and Lippold studied the corrosion resistance of dissimilar welds between duplex stainless steel alloy 2205 and carbon steel A36 using TIG welding process [18]. Both duplex stainless steel ER2209 and Ni-based alloy 625 filler metals were used to join this combination. They reported that the corrosion resistance of the welds made with 2209 filler metal improved with increasing heat input, probably due to higher levels of austenite and reduced chromium nitride precipitation.

However, there is very little published information available with regard to the effect of heat input on intergranular corrosion resistance of duplex stainless steel claddings. This paper focuses on an experimental study carried out on duplex stainless steel cladding of low carbon structural steel deposited by flux cored arc welding process. In this work, double-loop electrochemical potentiokinetic reactivation technique was employed to evaluate the intergranular corrosion resistance of the claddings. The effect of heat input on intergranular corrosion resistance is presented in graphical forms, which are very useful to improve the corrosion resistance of the claddings.

2.0 EXPERIMENTAL PROCEDURES

2.1 Weld Cladding Procedure

The experiments were conducted using UNIMACRO 501C programmable welding machine. Test plates of 200 X 150 X 20 mm size were cut from low carbon structural steel (IS:2062) plate and its surfaces were ground to remove the oxide scale before cladding. Flux cored duplex stainless steel welding wire (E2209T1- 4/1) of 1.2 mm diameter was used for depositing the weld beads. Chemical composition of the base metal and welding wire is given in **Table 1**.

Co_2 gas at a constant flow rate of 18 L min^{-1} was used for shielding. The experimental setup used consisted of a travelling carriage with a table for supporting the test plates. The welding gun was held stationary in a frame mounted above the worktable, and it was provided with an attachment for both up and down movement and angular movement for setting the required contact tip-to-workpiece distance and welding gun angle respectively. The experimental setup used is shown in **Fig. 1**.

The experiments were conducted by laying three beads using stringer bead technique with a constant overlap of 40%. An interpass temperature of 150° C was maintained during the experiments. The welding conditions used are given in **Table 2**. A typical cladded plate is shown in **Fig. 2**.

Table 1 : Chemical composition of base metal and welding wire

Material	Elements, wt. %									
	C	Si	Mn	P	S	Al	Cr	Mo	Ni	N2	Cu
IS: 2062	0.150	0.160	0.870	0.015	0.016	0.031	---	---	---	---	---
E2209T1- 4/1	0.023	0.760	1.030	0.024	0.002	---	23.14	3.05	9.22	0.13	0.09

Table 2 : Welding conditions

Specimen number	Welding current A	Welding speed, cm min^{-1}	Contact tip-to-workpiece distance, mm	Welding gun angle, degree	Arc Voltage volt	Heat input, KJ mm^{-1}
1	250	60	26	80	42	0.82
2	250	40	26	90	43	1.34
3	230	37	28	85	43.5	1.40
4	250	20	26	80	44	2.49

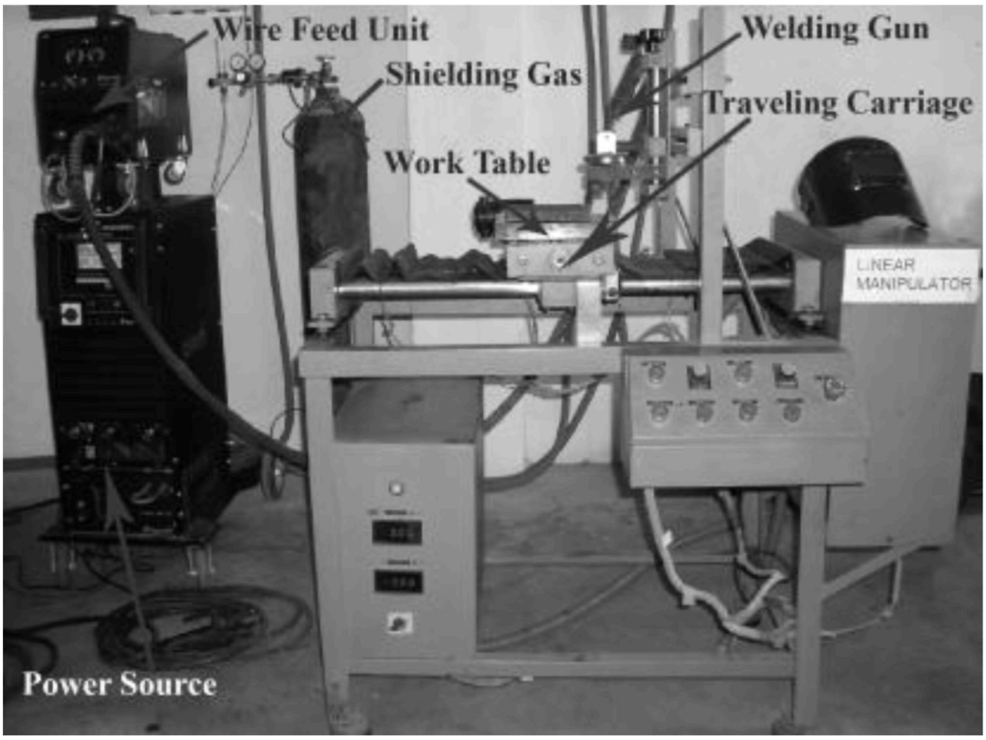

Fig. 1 : Weld cladding experimental setup

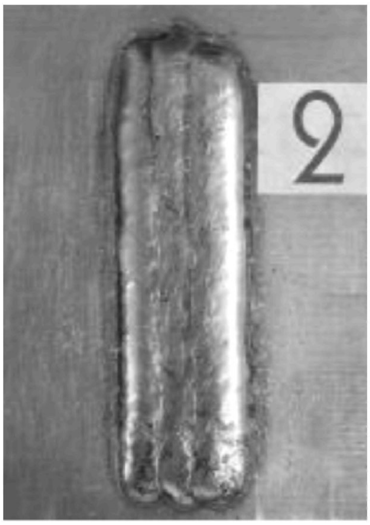

Fig. 2 : A typical cladded plate (Specimen No.2)

2.2 Intergranular Corrosion Test Procedure

The double-loop test was conducted as described by Akashi et al [8]. The surface of the test specimens were wet polished with 800-grit SiC paper as per ASTM G5-94 and rinsed thoroughly with distilled water [19]. IGC studies on the surface of the claddings were carried out using double-loop reactivation test as per the standard ASTM G5-94. The experimental setup consisting of an ACM Gill 5500 potentiostat /galvanostat instrument with a flat cell in three-electrode configuration were used. **Fig. 3** shows the corrosion study setup used for this study.

The flat cell consists of glass cylinder clamped horizontally between two end plates. One end plate houses the working electrode (duplex stainless steel clad metal) and other houses the counter electrode. The reference electrode is housed in luggin well, with a fixed Teflon luggin capillary protruding from the bottom of the well. Saturated calomel electrode (SCE) and platinum gauze were used as reference and counter electrodes respectively. Specimen was placed in the flat cell in such a way that polished surface of the clad portion was exposed to the test solution. The electrolyte used was 2 M H_2SO_4 + 0.5 M NaCl + 0.01 M KSCN solutions [12]. The test solution was maintained at temperature 30 ± 2° C. The polished weld specimen was allowed to settle for 30 minutes to determine the corrosion potential, which was near - 400 mV Vs SCE for duplex stainless steels. The specimen was polarized anodically to the potential of + 300 mV V_s SCE at a scan rate of 100 mV min^{-1}. As soon as the potential was reached, the scanning direction was reversed at the same scan rate as forward direction until corrosion potential was reached [9]. The maximum current for each loop was measured. I_a for the large anodic loop, which was generated first and I_r for the smaller loop generated during reverse scan (reactivation). A graph was drawn to visualize the peak of anodic and reactivation curve obtained from double-loop EPR test for measurement using analysis software provided with the instrument. Two test runs were carried out for each specimen and the average values of I_a and I_r were obtained. The double-loop EPR curves of the specimen cladded at different heat input conditions are shown in **Figs. 4 to 7**.

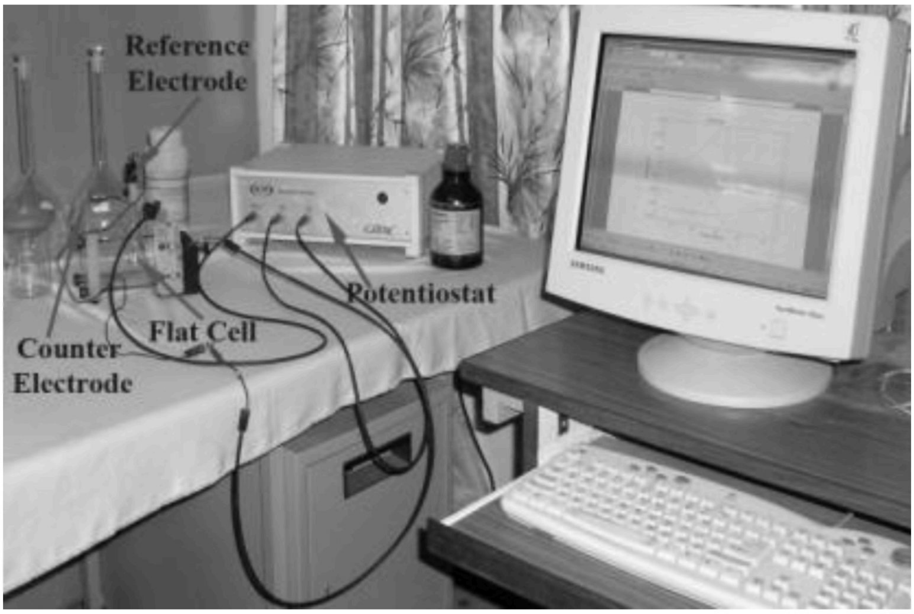

Fig. 3 : Experimental setup used for corrosion study

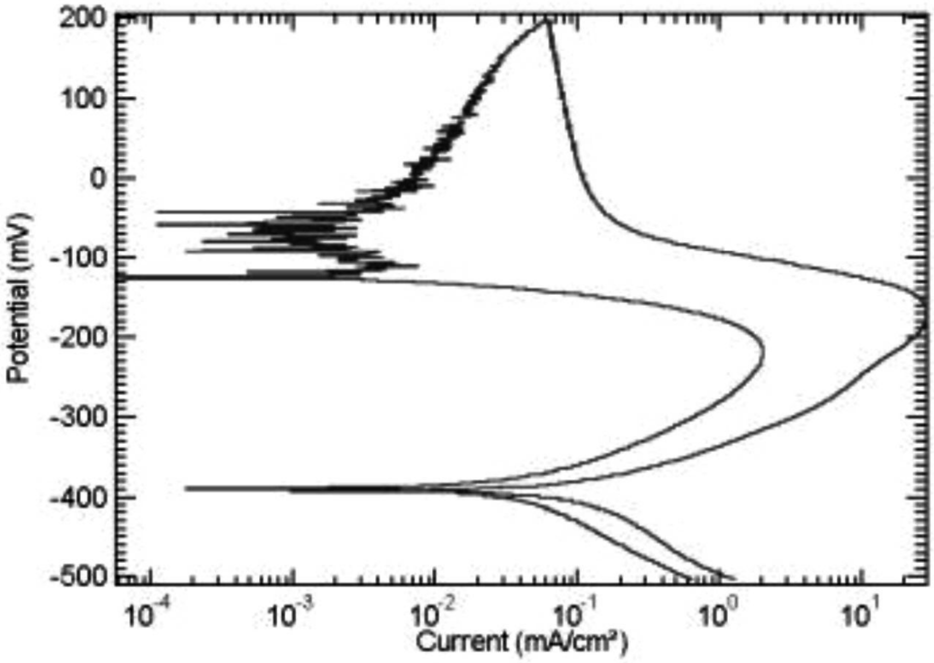

Fig. 4 : Double-loop EPR curve of the specimen cladded at 0.82 KJ mm^{-1} conditions

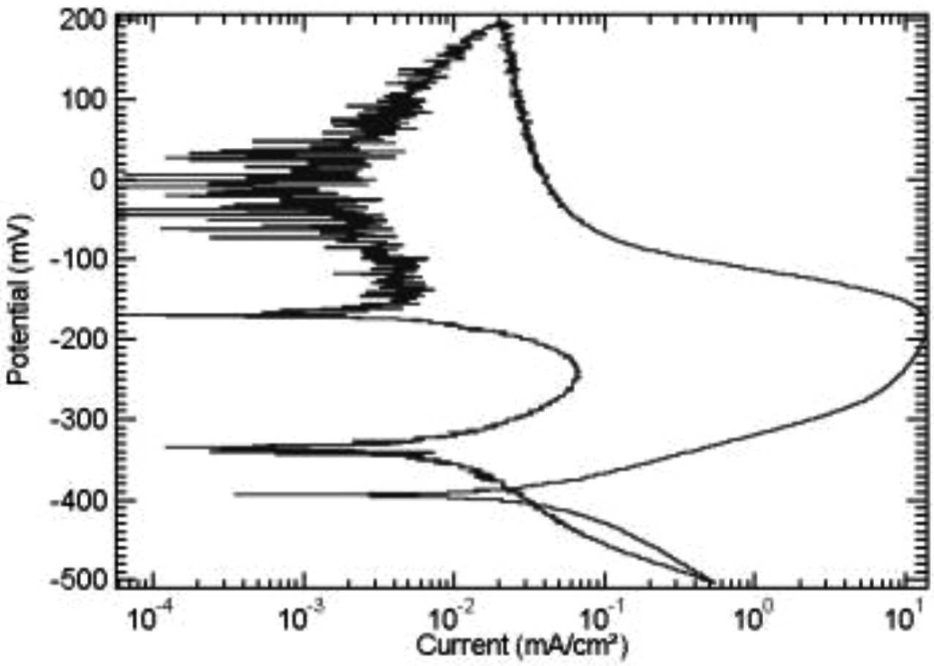

Fig. 5 : Double-loop EPR curve of the specimen cladded at 1.34 KJ mm^{-1} conditions

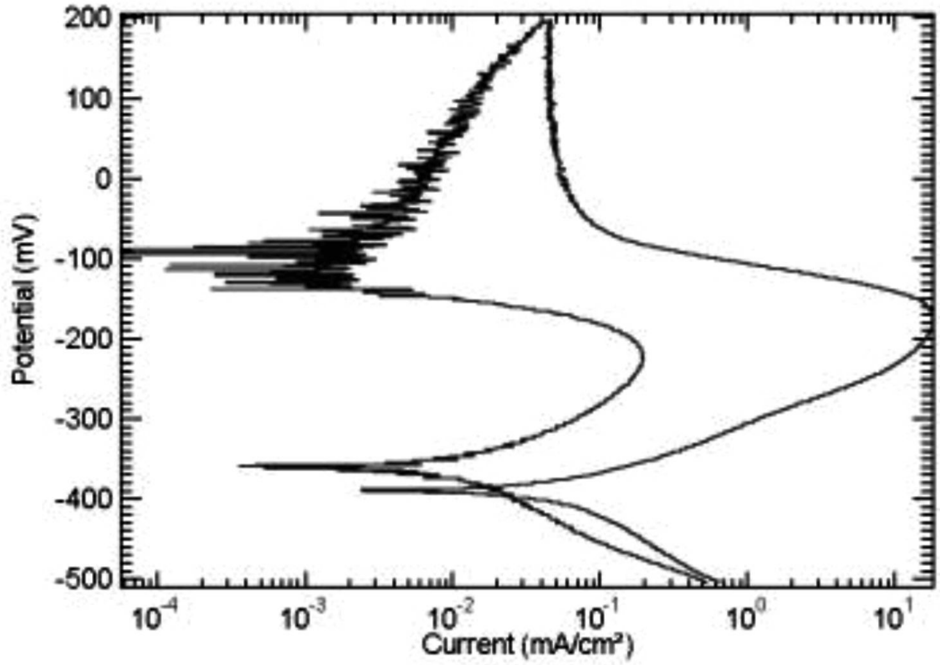

Fig. 6 : Double-loop EPR curve of the specimen cladded at 1.40 KJ mm^{-1} Conditions

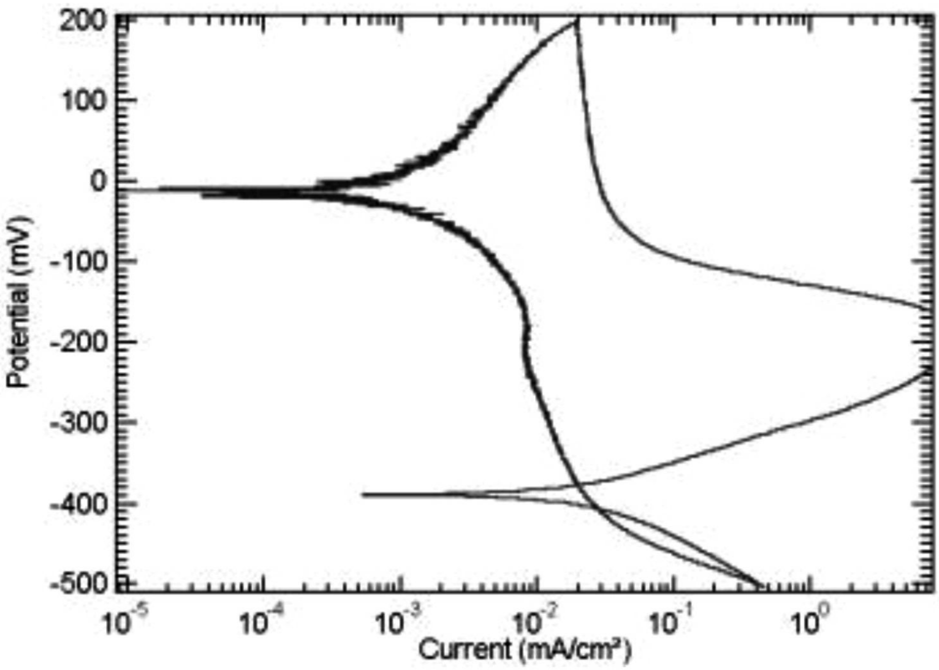

Fig. 7 : Double-loop EPR curve of the specimen cladded at 2.49 KJ mm^{-1} Conditions

3.0 RESULTS AND DISCUSSIONS

The maximum values of reactivation current density (I_r) and the anodic current density (I_a) measured from the curves are given in **Table 3**. The current ratio of the claddings deposited at high heat input conditions was well below the upper limit of 0.001, which indicated that they possessed good resistance to intergranular attack [19]. The corrosion behavior showed a remarkable improvement for high heat input welding parameters relative to the low heat input. The heat input is typically calculated as the ratio of power (i.e. voltage × current) to the velocity of the heat source (i.e. welding speed). The change in welding current, welding speed and arc voltage only affects the heat input but change in contact tip-to-workpiece distance and welding gun angle does not affect the heat input significantly.

Table 3 : Double- loop epr tests results of as-welded specimens

Specimen number	Activation current (I_a), μ A / cm²	Reactivation current (Ir), μA / cm²	Current ratio I_r / I_a
1	28.64	2.04	0.0712
2	17.38	0.088	0.0051
3	28.26	0.026	0.0009
4	7.81	0.0055	0.0007

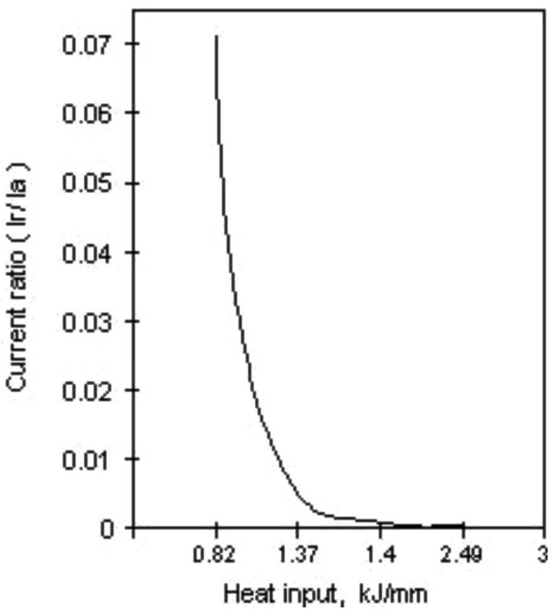

Fig. 8 : Effect of heat input on Intergranular corrosion resistance

The effect of heat input on current ratio (I_r/I_a) is shown in **Fig. 8**. From the figure it is evident that current ratio decreases with increase in heat input, which indicates increase in resistance to Intergranular corrosion of the claddings. This is due to increase in heat input mainly due to decrease in welding speed, which is given in **Table 2** and also the base metal had no chromium and nickel and had higher carbon content than that of the duplex stainless steel welding wire. Decrease in dilution due to decrease in welding speed results in increased chromium, molybdenum and nickel content when compared to low heat input claddings [1, 20]. The increase of chromium and nickel with decrease in dilution results in decreased current ratio (I_r/I_a) of the clad metals. The carbon content of the claddings is also low due to low dilution, which reduced the risk of IGC.

4.0 CONCLUSIONS

The effect of heat input on Intergranular corrosion resistance of duplex stainless steel clad deposits was investigated. The following are the conclusions derived from the above investigation. Double-loop EPR technique used to detect sensitization in duplex stainless steel was found to be quantitative, non-destructive, rapid and reliable method. The current ratio of the claddings deposited at high heat input conditions showed a marked improvement than the low heat input claddings. The current ratio decreases with rise in heat input, which increases the chromium, molybdenum and nickel content of the claddings thereby increased corrosion resistance.

ACKNOWLEDGEMENT

The authors wish to thank M/S Bohler welding; Austria for providing flux cored welding wire for this work. The financial support for this work from All India Council of Technical Education and University Grants Commission are gratefully acknowledged. The authors also wish to thank the managements of Coimbatore Institute of Technology and Kumaraguru College of Technology for having provided all the necessary facilities to carry out this work.

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