Scientific Journal of Impact Factor (SJIF): 4.14
e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406
International Journal of Advance Engineering and Research Development
Volume 3, Issue 12, December -2016

Study Of The Electro Slag Strip Cladding Process & Effect Of Its Parameters On Welding

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Abstract — *The paper focuses on the study of Electro Slag Strip Cladding (ESSC) process carried out in the industry for corrosion resistant overlay on the inner surface of the pressure vessel shells. The process principle, process initiation & process parameters of ESSC have been discussed. The welding parameters which are controlled by the welder during the process are current, voltage, speed, flux height, electrode, strip offset. There is a specified range of values for these parameters to be maintained. If this range is violated, then it will seriously affect the welding microstructure & ultimately the weld chemistry & strength. This paper discusses about how a change in these parameters affect the weld obtained.*

Keywords*- Dilution in ESSC, Electroslag Strip Cladding, Heat input in ESSC with stainless steel electrode, Magnetic steering device for strip cladding, Overlay welding for corrosion resistance, Parameters of ESSC, Stick-out & offset In ESSC, Weld cladding.*

I. INTRODUCTION TO WELD OVERLAY

Inner surfaces of heavy wall pressure vessels such as nuclear reactor or oil refinery plant are weld overlaid with stainless steel or nickel alloy to prevent corrosion or hydrogen attack. Overlay welding is performed by means of various methods, such as, Shielded Metal Arc, Submerged Arc, Gas Metal Arc or Plasma Arc Welding. However, these large-sized equipments with a large overlay area & tons of deposition require an efficient welding process. In overlay welding, not only a high efficiency, but also low penetration into the base metal i.e. less dilution are required [1]. Thus, Electro Slag Strip Cladding (ESSC) is the most preferred process for overlay welding. The principal object of such a product is to combine, at low cost, the desirable properties of the stainless steel and the backing material for applications where full-gage alloy construction is not required. While the stainless cladding furnishes the necessary resistance to corrosion, abrasion, or oxidation, the backing material contributes structural strength and improves the fabricability and thermal conductivity of the composite.

II. ESSC PROCESS PRINCIPLE

Electro Slag Strip Cladding basically works on Joule's Heating Law. The heat required to melt the strip, the slag-forming flux and the surface layer of the base metal is generated by resistance heating due to the welding current flowing through the molten conductive slag.

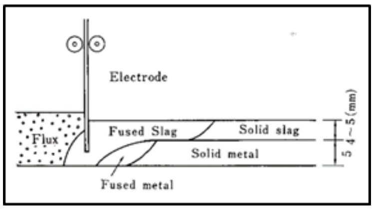

Fig. 1: Schematic Of ESSC Process [8]

III. PROCESS INITIATION

1. Initially, the strip & base metal are away from each other. Both the current & welding are off at this instance. Strip is cut at 45° angle.
2. Now, current (DCEP Polarity) is switched on. Electrode strip is lowered slowly & is made to touch the base metal (base metal). When the strip is a fraction of a millimeter above the base metal, a spark is noticed. Then, when the strip & base metal are in contact, the spark is not noticed now. Thus, current is now flowing from the strip into the base metal which is grounded.

3. Flux is fed from the hopper. Enough flux is fed so as to cover the strip-base metal interface from the environment.
4. Welding is turned on. Here there are two types of mechanisms depending on the welding head used. Both of these are automatically performed by the welding head :-
    a. The strip electrode is lifted & fed again by 2-3 mm. This produces an arc between electrode & w/p. This produces a very high temperature which melts the strip. This subsequently melts the flux surrounding the arc.
    b. A very high current is passed through the strip. Due to this, the current density at tip contact is very high & this melts the tip. This creates a minute gap between electrode & base metal. Thus, arc is formed which melts the strip & subsequently the flux.
5. Now, because of the arc, the strip has melted & flux is converted to electro-conductive molten slag.
6. Because of the electro-conductive nature of the molten slag, the current now flows through it & the electric circuit is as follows:-

Strip → Electro-conductive molten slag → Base metal → Ground

7. Thus, the arc is extinguished. This implies the following conditions:

$R(arc)=\infty$ & $I(arc)=0$ [3]

8. Now, current (I) is flowing continuously through the Electro-conductive molten slag having resistance (R), for time (t). Joule's heating [$Q=I^2Rt$] of molten slag takes place. Slag temperature is 2300˚C which is enough to melt the strip & base metal.
9. Thus, the strip further melts. As density of molten metal > density of molten slag, the molten metal goes down & adheres to base metal.
10. As the process progresses, the molten slag solidifies. Solidified slag is not electro-conductive. This solidified slag is removed by tapping with wire-brush.

Steps 8,9,10 go on continuously until the welding is stopped.

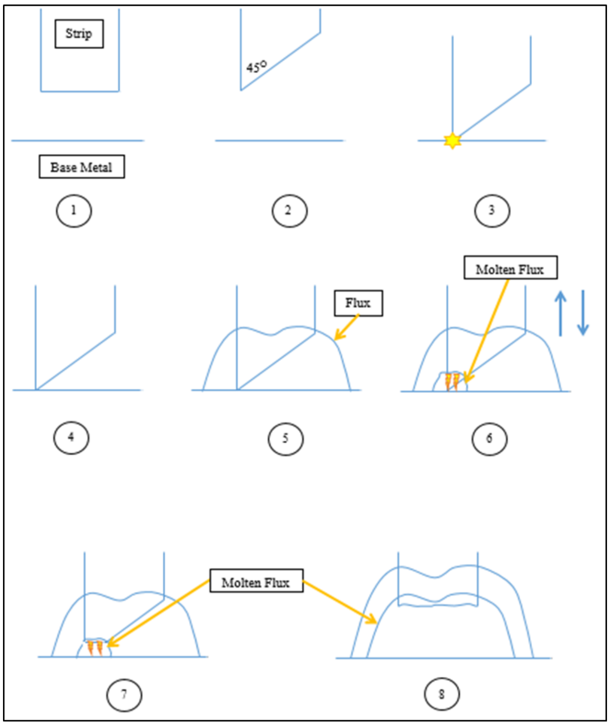

Fig. 2: ESSC Process Initiation

IV. PROCESS PARAMETERS

4.1. Current

a. Current is set in ESSC indirectly by varying the Wire-Feed speed in the Lincoln Electric NA-5 Controller.
b. It affects the rate at which the strip is melt & deposited on the base surface. This is because, heat input & heat generated in the pool increases with increasing current.
c. It varies with the strip width used so as to keep the current density in range of 40-43 A/mm^2 [3].
d. The magnitude of current used for different strips is as shown Table 1.

4.1.1. Consequences of too high current

a. Increasing current will increase the Lorentz force on the slag pool. This will lead to more & more coagulation of the pool from the edge toward the center. Thus undercut will increase.
b. To increase the current, the WFS has to be increased. Thus more strip material will be deposited per unit time.
c. Due to the increased strip melting & deposition into the pool, the heat transfer between the pool & base metal will increase, thus increasing the penetration levels & consequently decreasing the dilution.
d. Increased WFS will also lead to very thick & wide beads.
e. Very high current input may melt the strip just after the contact tip in the welding jaw & result in arcing.
f. Increased slag spatter due to increased turbulence in the pool flow [4].

4.1.2. Consequences of too low current

a. Incomplete melting of the strip, because the heat generated $Q=I^2RT$ will not be sufficient to melt the strip properly.
b. Due to this, the partially melted & thus partially adhered bead will appear on the base metal.
c. Also, due to the same reason, weld penetration will be less & fusion won't be proper, thus affecting the weld chemistry.
d. Due to less penetration, the dilution will increase, thus resulting in a crack-prone bead.

4.2 Voltage

a. It determines the arc length between the strip & base metal.
b. Reduction in voltage results in decrease in arcing distance. So, when using higher strips with higher current, the reduced voltage helps in avoiding arcing due to increased WFS during the process. Refer Table 1 for values of voltage for different strip widths & current levels.
c. Bead height & width will increase with increasing voltage due to increased heat input to the strip.

4.2.1. Consequences of too high voltage

a. The process becomes unstable.
b. Continuous arcing during the process will distort the bead by causing surface ripples on the surface.

4.2.2. Consequences of too low voltage

a. Strip electrode has a tendency to stick to base metal due to reduced heat input [4].
b. Due to this, the partially melted & thus partially adhered bead will appear on the base metal.

4.3 Weld Travel Speed

It is the linear velocity of inner cylindrical surface of the shell.

4.3.1. Consequences of too high welding speed

a. Viscous slag may not be able to keep up with the fast advancing strip.
b. This leads to unstable process & arcing may occur resulting in uneven & distorted bead profile.
c. Undercutting. Because the molten pool won't get enough time to travel to the bead toes by the influence of magnetic steering device.
d. Slag inclusions, porous weld may occur. High speed leads to low heat input per unit area, which leads to increase in solidification rate. So, the gases do not get enough time to escape. This is because the basicity index of the flux is not increased to fasten up the slag-metal reactions.
e. Low bead height & width.
f. Reduced time for effective heat transfer within the weld pool, but the penetration increases.
g. Dilution of the base material in the weld pool increases with the increase in welding speed, since the weight of deposited metal per unit length decreases while the cross section of the bead decreases very little. For the same value of current, the welding speed and the same arc voltage, the depth of penetration is greater and it also depends on the distance between contact tip-to-workpiece, and the size of electrode.
h. The dilution also increases with penetration [5]. This point is explained later in Section 4.8 in this paper.

4.3.2. Penetration v/s Weld Travel Speed & Effect Of Low Weld Travel Speed

a. When the weld travel speed is too low, the incoming electrode impinges on the previously melted metal itself in the molten pool. Here, the previously melted metal in the molten pool gives a cushioning effect to the incoming strip & thus causes the penetration to decrease. This is because the incoming heat is not being given entirely to the base metal due to the cushioning.
b. The reverse occurs when weld travel speed increases & hence penetration increases. Here, the incoming electrode impinges on the solid base metal through the slag. Here the molten pool does not give a cushioning effect as enough quantity of molten metal is not accumulated in the pool to give cushioning.
c. As we are not altering the WFS, the amount of incoming strip deposited does not change. This causes the bead height & width to decrease with increased penetration. Thus here as the penetration increases, the dilution also increases [5].

Table 1: Nominal Ranges Of Current, Voltage & Speed For Varying Strip Width

Strip Size (Width x Thk) (mm)	30 x 0.5	60 x 0.5	90 x 0.5	120 x 0.5
Current (A)	600-650	1200-1250	1800-1850	2400-2500
Current Density (A/mm²)	40-43.33	40-41.67	40-41.11	40-41.67
Voltage (V)	22-24	23-25	24-25	24-25
Weld Travel Speed (mm/min)	160-180	160-180	160-180	160-180

4.4 Heat Input

$$\textbf{Heat Input (kJ/mm}^2\textbf{)} = \frac{A\,V}{S\,W} \times \frac{60}{1000} \qquad [9]$$

where,

A = Current (amperes)
V = Voltage (volts)
S = Welding speed (mm/min)
W = Strip Width (mm)

$$R \propto \frac{1}{T_o H}$$

where,

R = Cooling Rate (^{O}C/sec)
T_o = Preheat Temperature (^{O}C)
H = Heat Input (kJ/mm^2)

a. As either the heat input or the preheat temperature increases, the rate of cooling decreases for a given base metal thickness [6].
b. These two variables interact with others such as material thickness, specific heat, density, and thermal conductivity to influence the cooling rate.
c. The cooling rate is a primary factor that determines the final metallurgical structure of the weld and heat affected zone (HAZ), and is especially important with heat-treated steels.
d. The increased heat input leads to weld solidification cracking, intergranular corrosion, knifeline attack [7].

4.5 Flux Burden

a. As a general rule, the depth of the flux should be between 0 and 5 mm more than the length of the electrode extension [5].
b. Less flux burden will result into arcing & unstable process, leading to improper bead full of surface ripples.
c. More flux burden will lead to slag inclusions, porous weld & slag pockets. This is because too much flux burden causes difficulty for the gases to escape from the weld pool.
d. As we increase the flux burden, more & more amount of flux is available at the weld pool for slag-metal reactions. This increases the weld dilution rate [5].
e. Flux is always dropped from the front of strip only, as viewed in the welding direction. If flux is dropped from the back, then the process won’t take place.

4.6 Electrode Stickout

a. The stick out is the length of the free strips electrode end from the contact jaws to the parent metal.
b. It may vary between 35 and 40 mm without affecting the stability of the process.
c. A variation with in this range does not influence bead geometry, penetration or dilution and deposition rate to any large degree.
d. When the stickout is increased, the longer length of the strip beyond the jaw contact-tip increases the resistance. It causes the strip to heat & is accompanied by reduction in current due to increase in resistance.
e. This reduced amperage supplied to the slag pool results in a decreased penetration due to reduced $Q = I^2RT$ in the slag pool.
f. But, due to the increased resistance & heating up of the strip, the strip melts easily. For the same input current, more strip will melt. Thus will result in a wider & thicker bead.
g. The decreased penetration along with wider & thicker bead will decrease the dilution [5], [10].
h. The HAZ decreases with an increase in the stickout & this causes reduced penetration & dilution.
i. However, too long a stickout results in poor weld bead shape, shallow penetration and an unstable arc as the strip may melt slightly above the slag pool & result in arcing.

4.7 Strip Offset & Base Metal Inclination

a. Practical data shows that penetration measured as the degree of dilution should exceed 5% on a flat surface & 10% for surfacing on a curved area in order to avoid incomplete fusion [4].
b. As the inclination is increased, the slag remains in contact for more & more time with the base metal. This increases the heat transfer between the molten pool & base metal & thus increases both the penetration & dilution. Both penetration & dilution increase simultaneously here because the deposition rate or WFS is unaltered.
c. Therefore, it is recommended that the parent metal should be placed in flat position for welding.
d. The strip electrode offset is set such that base metal inclination is 0-2^{O} uphill position & nearly flat position.
e. The strip offset is such that the molten slag solidifies by the time it reaches the BDC (Bottom Dead Center).
f. **If there is no offset** then, the molten pool will be at the BDC. Due to shell rotation & viscous nature of slag, it will be carried away forward the BDC by some distance & then due to gravity, it will again come back to the BDC.
g. This will distort the bead profile due to the uneven flow of the slag pool.
h. Also, the molten slag coming back to BDC will disturb the slag pool at the welding location.
i. There will also be increase in penetration & consequently dilution in no offset condition.
j. **If the offset is less than the specified range,** then also the conditions as no offset will persist, but to a lesser extent.
k. Here, the offset distance provided is not in match with the solidification rate of the slag. The offset distance here is not enough to ensure weld solidification upto the BDC.
l. **If the offset is in the specified range,** the offset distance is such that the weld solidification occurs upto the BDC.
m. The slag flow is also smooth & even resulting in a smooth & even bead profile.
n. Weld dilution is also proper giving the desired weld chemistry.
o. **If the offset is more than specified range,** this will result in an increase in inclination as shown in below.
p. Because of this, under influence of gravity, the molten slag pool will tend to run towards the BDC.
q. Due to curved surface of the shell, this will lead to lack of fusion or disbonding between the base metal & weld metal.
r. This is because due to running away of molten slag, there is less time for effective heat transfer between the weld pool & the base metal so as to effectively penetrate the weld in the base metal.

Uphill Welding [4]:
- Thicker beads.
- Convex beads.
- Narrower beads.
- Deeper ditch in the overlap region.

Downhill Welding [4]:
- Thinner beads.
- Concave beads.
- Wider beads.

Thus, in ESSC we prefer uphill welding.

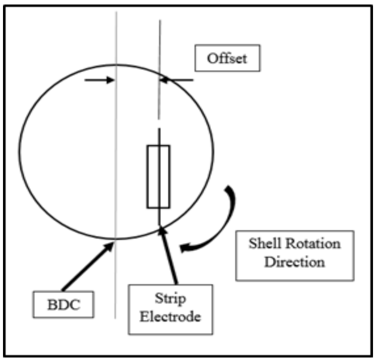

Fig 3: Strip Electrode Offset During ESSC Overlay Inside Shell.
BDC: Bottom Dead Center

4.8 Dilution In ESSC

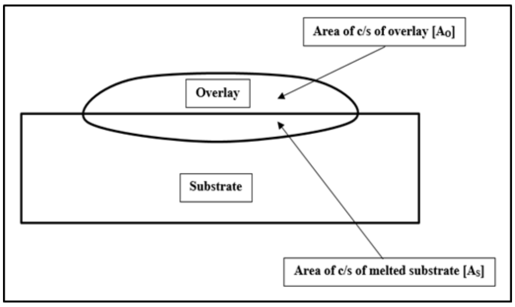

Fig 4: Cross-Section Of ESSC Weld Bead

a. In weld overlay cladding, our primary concern is to obtain the specified chemistry at a minimum height from the fusion line [4].
b. This is controlling factor, which determines the height of weld overlay required for meeting the specified cladding chemistry requirement of the customer.
c. A low dilution is beneficial because it allows for the desired properties such as wear and corrosion resistance of the surfacing materials to be maintained in the cladding.

$$\textbf{\% Dilution} = \frac{A_S}{A_O + A_S} \times 100$$

$A_O = R/DV$

where,

R = Deposition Rate
D = Strip Electrode Density
V = Travel Speed

$A_S = P \times W$

where,

P = Average Penetration Depth
W = Strip Electrode Width

$$\textbf{\% Dilution} = \frac{P\,W}{\frac{R}{D\,V} + P\,W} \times 100$$

- As current increases, the deposition rate (R) increases because of more heat generated as per Joule's Law.
- Also, the penetration (P) increases, but by a lesser value relative to R.
- From the formula of dilution, this **increase in current leads to reduction in dilution**, other parameters kept constant.
- As the weld travel speed (V) increases, the penetration (P) also increases.
- From the formula of dilution, this **increase in the weld travel speed leads to increase in dilution,** other parameters kept constant.
- Increase in voltage negligibly increases both the weld penetration & dilution. This increase is due to a slight increase on the heat input (increasing the penetration) & WFS (strip inflow rate into the pool) kept constant (leading to direct relationship between penetration & dilution).

V. MAGNETIC STEERING DEVICE

a. When magnetic control is not applied, a part of welding current flows in a weld pool & forms a magnetic field. As per Fleming's Left hand Rule, force acts on the center of the weld pool from both sides of the pool.
b. As a result, the width of bead is narrowed & undercut is easily generated on both sides of the bead.

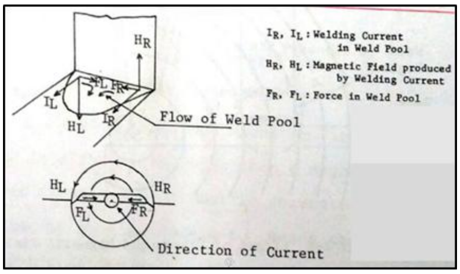

Fig 5: Principle Of Undercut Without Magnetic Control [7]

c. The generation of undercut is prevented by applying a forced magnetic field to a weld.
d. A magnetic field which is slightly stronger than that produced by the current flowing in the weld pool is generated & flown in an opposite direction by a magnet.

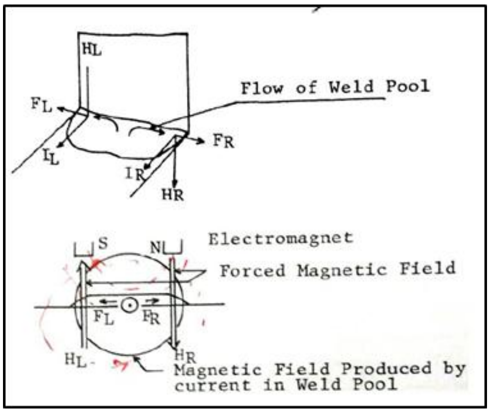

Fig 6: Effect Of Forced Magnetic Field [7]

e. Beads can be extended by changing a force acting on a weld pool from the center of the pool to both sides.
f. With the auxiliary steering magnets switched on, the width of the bead will increase by 1 to 2 mm; the depth is reduced accordingly since the filler material will be pulled toward the outer edges.
g. The South Pole is always place at the left side when viewed in the welding direction as in Fig. 6.
h. If the positions of North & South poles are reversed, then condition opposite to that shown in Fig. 6 will occur. This will lead to increased undercuts.
i. The positioning of the magnets is important to have the desired effect on the slag pool.
j. If there is undercut to one side, either increase the current on that side or decrease the current on the other side to provide a suitable balance between the two magnetic fields.
k. The bead wetting angle should be around $45^O – 60^O$ for perfect bead.
l. If the current in magnetic steering is low, then the bead wetting angle also increases resulting in a steep bead profile at the bead toes. This causes lack of fusion at the bead overlap region. This is because:
Lorentz Force due to weld pool > Lorentz Force due to magnets.
m. If the current in magnetic steering is high, then the bead wetting angle decreases resulting in a very less slope at the bead toes. This gives rise to grooves at the overlap region. This is because:
Lorentz Force due to magnets > Lorentz Force due to weld pool.

VI. CONCLUSION

The corrosive service conditions of a heat exchanger make it essential to give due considerations to the corrosion resistant properties. But due to the lack of economic feasibility in fabricating the pressure vessel of corrosion resistant material, weld cladding is preferred. The phenomenon of Electro Slag Strip Cladding has been deeply studied. The welding parameters which are controlled by the welder during the process bear importance with respect to the weld quality & properties i.e. bead profile, weld chemistry, strength etc. The settings of magnetic steering device are very crucial with respect to the bead overlap. These magnets help to reduce the influence of the Lorentz force generated due to the weld pool & achieve a proper & defect-free bead overlap. Thus, the decision of determining the welding parameters has to be done after giving due consideration to its consequences on the weld quality.

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