CHAPTER 1

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1.1. Overview

The demand for structural steel has increased globally as well as in India in the past few years (Morrison, 2001; Khanna and Jha, 2005; Sato and Hara, 2011) and with compound annual growth rate (CAGR) of 2 to 3% in world (WSA, 2013) and 10% in India in past five years (Khanna and Jha, 2005; MBSS, 2012). The steels used for structural applications in different forms of sections, plates, bars, hollow sections are known as structural steels. Structural steels are graded by quality standards and specifications, chemical composition, mechanical and technological properties etc. Structural steels applications include automobile industry, ship building, pipelines, pressure vessels, building construction, bridges, transmission towers, storage tanks etc. Structural steels may be classified as carbon steels, high-strength low-alloy (HSLA) steels, heat-treated carbon steels and heat-treated constructional alloy steels (Brockenbrough and Merritt, 2011). The demand for structural steel has increased even more by the requirements of suitable pipeline material for transporting the oil and natural gas on long distances under severe environments in oil and natural gas industries. Pipeline materials not only must possess high tensile strength and toughness but also should be possessing higher strength to weight ratio, economical and safe option to carry these materials (Mohtadi-Bonab et al., 2013; Hashemi and Mohammadyani, 2012). Among above mentioned steels; steels having minimum yield strength greater than 275 MPa (40 ksi) in the hot-rolled condition are known as high-strength low-alloy (HSLA) steels (Brockenbrough and Merritt, 2011) which become suitable material for pipeline steel. Typically, HSLA steels are low-carbon steels containing maximum carbon content 0.2%, containing up to 1.5% Mn, strengthened
by small additions of alloys columbium, copper, vanadium, niobium or titanium such that the total alloy content is less than 2% (Morrison, 2000; Kou, 2003).

The history of development of HSLA steels (Morrison, 2000) reveals that earlier structural steels were of the C-Mn type. These steels were containing relatively high carbon and manganese contents which led to welding problems and subsequent structure failures. By microalloying these C-Mn steels such welding problems were greatly reduced. Niobium, vanadium and titanium are strong carbide and nitride formers which tend to hinder the movement of grain boundaries, thus reducing the grain size by making grain growth more difficult. The reduction in grain size in HSLA steels increases their strength and toughness at the same time.

Welds from the exterior columns fabricated from structural steels (HSLA Steels) of the World Trade Center towers were evaluated after aircraft impact (Banovic and Siewert, 2006). Failure occurred in this region due to the lower cross-sectional area of the plate and the degraded HAZ mechanical properties (i.e., ductility, toughness with respect to the base plate of HSLA Steels) (Gayle, 2005).

Different authors have classified HSLA steels in different categories. Cardarelli (2008); Kou (2003) grouped HSLA steels into four classes as follows:

1) High-strength low-alloy steels
2) Heat-treated carbon steels
3) Heat-treated low-alloy steels
4) As-rolled carbon-manganese steels

Davis (2001) divided HSLA steels into six categories:

1) Weathering steels, which contain small amounts of alloying elements such as copper and phosphorus for improved atmospheric corrosion resistance and solid-solution strengthening.
2) Microalloyed ferrite-pearlite steels, which contain very small (generally, less than 0.10%) additions of strong carbide or carbonitride forming elements such as niobium, vanadium, and/or titanium for precipitation strengthening, grain refinement and possibly transformation temperature control

3) As-rolled pearlitic steels, which may include carbon-manganese steels but which may also have small additions of other alloying elements to enhance strength, toughness, formability and weldability

4) Acicular ferrite (low-carbon bainite) steels, which are low-carbon (less than 0.05% C) steels with an excellent combination of high yield strengths (as high as 690 MPa), weldability, formability and good toughness.

5) Dual-phase steels, which have a microstructure of martensite dispersed in a ferritic matrix and provide a good combination of ductility and high tensile strength

6) Inclusion-shape-controlled steels, which provide improved ductility and through-thickness toughness by the small additions of calcium, zirconium or titanium or perhaps rare earth elements so that the shape of the sulfide inclusions is changed from elongated stringers to small, dispersed, almost spherical globules

The material investigated in the present work is pipeline HSLA steel of grade API 5L X65 with yield strength of 448 MPa (65 ksi) and ultimate tensile strength of 531 MPa (77 ksi) (API, 2000). The selected X65 steel is a C-Mn steel with niobium (Nb), titanium (Ti) and vanadium (V) as primary micro-alloying elements. The low sulphur (S) and phosphorus (P) contents (0.01% each by weight) as well as the higher amounts of silicon (Si) content (0.17% by weight) is an example of clean steel (Refer Table 4.5: Chemical composition of base metal and electrode wire provided in in Chapter 4: Experimentation).
In oil and gas industries, submerged arc welding (SAW) is the only primarily used process to weld high thickness, large distance structural oil pipes (Jindal et al., 2013). SAW is used due to its inherent qualities like easy control of process variables, smooth finish, prevention of atmospheric contamination of weld pool, leak proof joints and ease of automation in welding of pipes (Parmar, 1992; Houldcroft, 1989; Murugan and Gunaraj, 2005; Khanna, 1999; Chai and Eagar, 1981; Gülenç and Kahraman, 2003). For submerged arc welding of such materials other problems like the selection of suitable welding consumables and parameters come into existence. Among all the problems encountered in welding; cold cracking or hydrogen induced cracking (HIC) or delayed cracking is the most serious and the least understood of all weld cracking problems particularly in the welding of high strength steels. Cracks may occur in the weld metal or HAZ because the stress at that point in the weldment exceeds at the ultimate tensile strength or ultimate shear strength of the base metal or weld metal (Davies and Garland, 1975; Lees, 1946; Singer and Jennings, 1947). HIC is promoted by the conditions; unacceptable diffusible hydrogen content, high restraint tensile stress, high hardness or a susceptible microstructure, and a temperature ranging between –100 and 100°C (Yurioka and Suzuki, 1990; Maroef et al., 2002). In spite of technological advances in the control of HIC, such as the use of lower carbon and hydrogen levels in the development of welding consumables even then HIC is not eliminated (Hart, 1986; Lundin, 1993).

Welding consumables of submerged arc welding include electrode wire and flux. Literature (Pandey et al., 1994; Kanjilal et al., 2006; Burck et al., 1990; Paniagua-Mercado et al., 2007; Kanjilal et al., 2005; Jindal et al., 2013; Kanjilal et al., 2007; Paniagua-Mercado et al., 2005) suggests that flux is the most important welding consumable which plays a main role in the stability of the arc and in deciding the chemical composition and hence the mechanical properties of the final weld deposit although the quality of the weld
may be also affected by the care and handling of the flux (O'Brien and Guzman, 2004). The fluxes for submerged arc welding of high-strength low-alloy (HSLA) steels are not readily available; flux compositions are not clear and patented. Previous work (Murugan and Gunaraj, 2005; O'Brien and Guzman, 2004) suggests that mechanical strength of welds is also influenced by the weld bead geometry in SAW. The study of Chai and Eagar (1980) indicates that weld metal chemistry is primarily dependent on weld metal flux composition and independent of operating parameters. The study also showed that weld bead geometry is dependent on weld parameters only and independent on flux composition. So selection of the optimum process variables and control of weld bead shape has become essential.

The present work aims at the design, development and optimization of flux mixtures for submerged arc welding of HSLA pipeline steel (API 5L X65) at optimized welding parameters.

1.2. Submerged Arc Welding (SAW) Process

1.2.1. Description of process

Submerged arc welding (SAW) derives its name from the fact that the arc is hidden under a heavy coating of granular mineral material or flux. Submerged arc welding produces coalescence of metals by heating them with an arc between a bare metal electrode and the workpiece (Parmar, 1992; O'Brien and Guzman, 2004). The arc, electrode wire and molten metal are “submerged” in a blanket of granular fusible flux that contains appropriate deoxidisers, cleansers and other desired fluxing ingredients. The dry granular flux is fed continuously from a hopper through a tube placed slightly ahead of the arc zone. Automatic operations are usually equipped with a vacuum system to pick up the unfused flux to be used again. The slag that forms on the weld bead normally peels off on its own or alternatively can be detached with the help of a chipping hammer.
The submerged arc welding process setup has been illustrated in Figure 1.1 and process has been described in Figure 1.2.

![Block Diagram of Submerged Arc Welding Setup](image)

**Figure 1.1: Block Diagram Showing Components of Submerged Arc Welding Setup**
(Parmar, 1992)

Factors that determine whether to use submerged arc welding include (O’Brien and Guzman, 2004):

a. The chemical composition and mechanical properties required of the final deposit
b. Thickness of base metal to be welded
c. Joint accessibility
d. Position in which the weld is to be made
e. Frequency or volume of welding to be performed

The process may be manual, semiautomatic, or fully automatic, although its main application today is with fully automatic systems, primarily for plate and structural work. Many types of fixtures and positioning equipment are available or can be built to satisfy this requirement.
1.2.2. Equipment for submerged arc welding

Automatic submerged arc welding setup consists of (Parmar, 1992, Linnert, 1994):

1) Welding power source
2) Wire feeder and a control system
3) An automatic welding head and flux hopper with flux feeding mechanism
4) Travel mechanism which usually consists of a travelling carriage and the rails.
5) Optional equipment includes flux recovery systems and positioning or manipulating equipment.
6) Main consumable materials required for SAW-electrode wire and fluxes.

1) Welding power source:

Power supply suitable for submerged arc welding is either DC or AC power supply. DC power supply may be a transformer-rectifier or a motor or engine generator type and AC are generally of transformer types, both providing a constant voltage (CV) or a constant current (CC) output.

2) Wire feeder and a control system:

The control systems used for semiautomatic submerged arc welding are simple wire feed speed controls. Controls used with constant-voltage (CV) power supplies maintain a constant wire feed speed while constant-current (CC) power supplies monitor the arc voltage and adjust the wire feed speed to maintain a constant voltage.

3) Welding head and flux feeding mechanism:

A submerged arc welding head comprises the wire feed motor and feed roll assembly, the torch assembly, contact tip and accessories for mounting and positioning the head. A flux nozzle is usually mounted on the weld head, to deposit the flux either slightly ahead of or concentric with the welding wire. Flux feed is provided by a small, gravity fed flux hopper mounted on the torch.
4) Travel mechanism
Weld head travel in SAW is generally provided by a tractor-type carriage, a side beam carriage or a manipulator. A tractor-type carriage provides travel along straight or gently curved weld joints by riding on tracks set up along the joint or by riding on the work-piece itself. The weld head, control, wire supply and flux hopper are generally mounted on the tractor.

5) Optional equipment:
Optional equipment includes flux recovery units, positioners and fixtures. Flux recovery units are frequently used to maximize flux utilization and minimize manual clean-up by removing unfused flux and recirculating flux back to a hopper for reuse.
Commonly used positioners include: Head-tailstock units, turning rolls, to rotate cylindrical parts under the weld head, tilting-rotating positioners, to bring the area to be welded on irregular parts into the flat position.

6) Consumable materials-electrode wire and fluxes:
Electrode wire produce weld deposits matching carbon steel, low alloy steel with carbon steels, special alloy steels, stainless steels, nickel alloys and special alloys for surfacing applications. Steel electrodes are usually copper coated which provide good shelf life, decreases contact tube wear and improves electrical conductivity. Submerged arc welding electrodes vary in size from 1/16 to 1/4 inch (1.6 to 6.4 mm) in diameter.
Flux is an essential aspect of the submerged arc welding process and it serves the following purposes (O'Brien and Guzman, 2004).

i. The portion of the flux which melts floats as a liquid blanket over the molten metal; protects it from the deleterious effects of surrounding atmosphere thereby reducing the pickup of oxygen and nitrogen.
ii. It acts as a good insulator and concentrates heat within a relatively small welding zone, thus improving the fusion of the molten metal from the welding electrode and the parent material.

iii. It acts as a cleanser for the weld metal, absorbs impurities and adds alloying elements such as manganese and silicon.

iv. Owing to flux, the weld metal is not only clean but it is also denser and hence has excellent physical properties.

v. The blanket of flux improves the process efficiency by reducing spatter and burning losses, which are unavoidable with an ordinary open arc.

1.2.3. Composition and chemical classification of SAW fluxes

The constituents of fluxes are basically raw materials of geological origin based on silica, silicates, limestone, clay, oxides, fluorides and other minerals. Generally a SAW flux consists of quartz (SiO₂), hausmanite (Mn₃O₄), corundum (Al₂O₃), periclase (MgO), calcite (CaCO₃), fluorite (CaF₂), limestone (CaO), zirconia (ZrO₂), cryolite (Na₃AlF₆), dolomite (CaMg(CO₃)_2), ferro-silicon (FeSi₂), magnesite (MgCO₃), rhedenite (MnSiO₃), rutile (TiO₂), wellastonite (CaSiO₃), zircon (ZrSiO₄) as well as oxides of barium, sodium, potassium and iron i.e. BaO, Na₂O, K₂O and FeO. It may consist of all these elements or some of them in the desired proportions (Parmar, 1992). Each element induces different characteristics in the welding flux, thus manipulation of their proportions gives the suitability of flux to meet the requirements. Depending upon the amount of different constituents a flux may be acidic, basic or neutral which is determined by basicity index (BI) of the flux. Basicity index (BI) is defined as the ratio of basic oxides to acidic oxides given by Equation 1.1 (Plessis et al., 2007; Linnert, 1994) as follows:

\[
BI = \frac{[\text{CaO} + \text{MgO} + \text{CaF}_2 + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{BaO} + \frac{1}{2}(\text{MnO} + \text{FeO})]}{[\text{SiO}_2 + \frac{1}{2}(\text{TiO}_2 + \text{ZrO}_2 + \text{Al}_2\text{O}_3)]} \tag{1.1}
\]
A flux is considered acidic if BI < 1, neutral for BI between 1.0 and 1.5, basic for BI between 1.5 and 2.5 and highly basic for BI > 2.5 (Linnert, 1994).

1.2.4. Physical classification of SAW fluxes

 Fluxes for submerged arc welding may be of two main types (Linnert, 1994) which are as follows:

 1) Fused fluxes
 2) Agglomerated fluxes

 1) Fused fluxes:

As the name implies a fused flux is prepared by fusing the ingredients together in a furnace and grain sized as required. The most commonly used fluxes are fused fluxes. These are manufactured from minerals like sand (SiO₂), manganese ore (MnSiO₃), dolomite (CaMg(CO₃)₂), fluorspar, chalk (CaCO₃) etc. It is free from moisture and is non-hygroscopic. In appearance the grains of fused fluxes are transparent particles from yellow to reddish brown in colour.

 2) Agglomerated fluxes:

Agglomerated fluxes include ceramic fluxes which are prepared by mixing together the ingredients and bonding the grains with water glass (sodium silicate). These fluxes contain ferro-alloys (ferro-manganese, ferrosilicon and ferro-titanium) and provide a high content of silicon, manganese and other alloying elements in the weld metal.

Fused fluxes have been gradually replaced with agglomerated fluxes which now represent 95% of the volume of welding fluxes used (Pokhodnya, 2002). Agglomerated fluxes produce weld deposits of better ductility and impact strength (Quintana et al., 2003; Linnert, 1994) as compared with fused fluxes. These are preferred as they give high percentage of alloy transfer from the flux and less flux is melted for a given amount of weld deposit under identical welding parameters as compared to fused fluxes for strip
cladding process also (Han and Sun, 1998). Agglomerated fluxes react with moisture giving weld metal porosity at even low moisture level hence they require more thorough drying before use. So these fluxes should be stored in hermetically sealed containers and calcined before use.

1.2.5. Process variables of SAW

The process parameters of SAW are as follows (Parmar, 1992; O’Brien and Guzman, 2004; Linnert, 1994):

1) Welding current
2) Welding voltage
3) Welding speed
4) Type of flux and grain size of flux
5) Electrode diameter
6) Electrode stick-out
7) Type of electrode

Out of above process variables in submerged arc welding include important process variables; welding current, arc voltage and welding speed. However, the weld bead geometry is also affected considerably by type of flux and grain size of flux, electrode diameter, electrode stick-out, the kind of current and polarity, electrode-to-work angle, inclination of the workpiece (uphill or downhill), joint edge preparation and width and depth of the layer of flux.

1) Welding current:

Welding current is the most influential variable because it controls the rate at which the electrode is melted and therefore the deposition rate, the depth of penetration and the amount of base metal melted.

The effects of welding current are as follows:

i. Increasing welding current increases penetration and melting rate.
ii. Excessively high welding current produces a digging arc and undercut or a high and narrow bead.

iii. Too low welding current produces an unstable arc.

2) Welding voltage:
Welding voltage varies the length of the arc between the electrode and the molten weld metal. With the increase in arc length the arc voltage increases and thus more heat is available to melt the metal and the flux.

Excessively high-arc voltage will:

i. Produce a wide bead shape that makes slag removal difficult in groove welds.

ii. Produce a concave shaped weld

iii. Increase undercut along the edge (s) of fillet welds

Lowering the voltage will:

i. Produces a “stiffer” arc, which improves penetration in a deep weld groove and resists arc blow.

ii. An excessively low voltage produces a high, narrow bead and causes difficult slag removal along the bead edges.

3) Travel speed:
Power or heat input per unit length of weld is decreased when travel speed is increased and less filler metal is applied per unit length of weld resulting in less weld reinforcement hence weld bead becomes smaller.

Excessive speed promotes undercutting, arc blow, porosity and uneven bead shape. Relatively slow travel speeds provide time for gases to escape from the molten metal thus reducing porosity. Excessively slow speeds produce a convex bead shape which is subject to cracking, excessive arc exposure which is uncomfortable for the operator and a large molten pool flows around the arc resulting in a rough bead and slag inclusions.
1.3. Organization of the Thesis

Thesis has been divided into six chapters; chapter wise breakup of the thesis is given below:

Chapter 1 outlines the brief introduction about the thesis work, description of submerged arc welding (SAW), equipment for process; composition, chemical and physical classification of SAW fluxes, process variables of SAW, introduction and classification of structural steel.

Chapter 2 presents literature review on the previous published literature on weld bead geometry parameters, on weld bead/weldment properties due to welding parameters and flux composition variation and on flux design. The gaps identified in the literature have been discussed.

Chapter 3 discusses the problem formulation and plan of experimentation.

Chapter 4 discusses extreme vertices design for formulation of fluxes and response surface methodology (RSM)-central composite design (CCD) technique for optimization of weld parameters. ANOVA technique for data analysis and desirability function for multi response optimization has been described in this chapter.

This chapter discusses the procedure for deciding individual flux constituents; their upper and lower limits; selection of three independent weld parameters; welding current, arc voltage and weld speed and their levels for optimization of weld parameters.

The details of experimental set-up, preparation of fluxes, conduction of experiments, procedure and equipment for measurement of different output characteristics of the welded samples have been discussed.

Chapter 5 presents results of optimization experiments for welding parameters and flux compositions. Development of mathematical models, their analysis, 3-D response surface graphs for bead width, bead height, area of reinforcement, area of penetration, form factor...
and dilution and the optimal levels of weld parameters; welding current I, arc voltage V and weld speed S have been also presented in this chapter.

Mathematical models for ultimate tensile strength, percentage elongation, impact strength, microhardness and weld metal element content for welded specimens in terms of flux mixtures have been presented, analyzed and optimized. Contour plots indicating predicted values of output performance characteristic have been represented. Microstructures of welded samples and XRD analysis of slag samples have been also discussed in this chapter.

Chapter 6 contains the conclusions of the research work carried out in the thesis. Some suggestions for future work on the related topics have been also enumerated at the end of this chapter.