CHAPTER 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK
6.1. Conclusions

- The mathematical models for various weld bead geometry parameters; bead width, bead height, area of reinforcement, area of penetration, form factor and dilution have been developed in terms of welding parameters; welding current $I$, arc voltage $V$ and weld speed $S$. These models may be readily used for getting desired weld properties in submerged arc welding of API 5L X65 and other HSLA steels. The mathematical models for various bead geometry parameters are as follows:

Bead width, $W = -34.23506 + 0.03861I + 1.05188V + 0.86384S - 0.00181IS$

Bead height, $h = 99.4263 - 0.03567I - 4.82765V - 1.33816S - 0.00006I^2 + 0.05192V^2 + 0.00347IV + 0.00083IV + 0.02083VS$

Area of reinforcement, $A_r = 591.357 - 1.07043I - 18.1081V - 1.33951S + 0.03843IV$

Area of penetration, $A_p = -1456.73 + 106.425V - 2.69879S - 1.77448V^2$

Form factor = $-7.01638 + 0.00242I + 0.29375V + 0.22972S + 0.00002I^2 - 0.00046IV - 0.00039IS$

Dilution = $-915.0909 + 0.1854I + 58.5578V + 4.9334S - 0.0002I^2 - 0.8602V^2 - 0.0766S^2 - 0.0053IV + 0.0070IS - 0.1854VS$

- Welding current has increasing effect on bead height, area of penetration and dilution but decreasing effect on bead width and form factor whereas arc voltage has increasing effect on all the weld bead geometry parameters; bead width, bead height, area of penetration, area of reinforcement, form factor and dilution.
- Bead width, bead height, area of reinforcement, area of penetration and dilution decrease but form factor increases with increase in welding speed.
- Interaction plots among welding parameters for weld bead geometry parameters indicate interaction effect of welding parameters is also important along with the main effect of these parameters.
- Bead width is affected by interaction among welding current and weld speed only whereas bead height is affected by interaction among all the welding parameters; welding current, arc voltage and weld speed.
- Area of reinforcement is affected by interaction among welding current and arc voltage only whereas area of penetration remains unaffected by interaction among any of the welding parameters; welding current, arc voltage and weld speed.
- Dilution of weld bead is affected by the interaction among all the welding parameters; welding current, arc voltage and weld speed but form factor is affected by interaction between welding current and arc voltage and interaction between welding current and welding speed.
- Optimum welding parameters for suitable weld bead geometry have been suggested for submerged arc welding of structural pipe steel (API 5L X65) which are as per table:

<table>
<thead>
<tr>
<th>Welding Parameters</th>
<th>Welding Current, I (A)</th>
<th>Arc Voltage, V (V)</th>
<th>Weld Speed, S (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>410</td>
<td>30.4</td>
<td>21.2</td>
</tr>
</tbody>
</table>

- The mathematical models for mechanical properties of weld metal have been developed in terms of individual and binary flux mixtures for welding of structural steel. The developed models have been validated by conducting confirmatory experiments and mean percentage error for ultimate tensile strength, percentage
elongation, impact strength and microhardness are 3.3%, 3.9%, 3.9% and 4.9% respectively. The developed mathematical models are as follows:

Ultimate tensile strength, $\text{UTS} = -4.9531 \text{CaO} + 7.6824 \text{Al}_2\text{O}_3 + 2.7335 \text{CaF}_2 + 6.0239$ \n$\text{MgO} + 0.0344 \text{CaO.Al}_2\text{O}_3 + 0.5013 \text{CaO.CaF}_2 + 0.3182 \text{CaO.MgO} + 0.1326$ \n$\text{Al}_2\text{O}_3.\text{CaF}_2 -0.0218 \text{Al}_2\text{O}_3.\text{MgO} -0.0197 \text{CaF}_2.\text{MgO}$ 

Percentage elongation, $\% \text{el.} = -1.2589 \text{CaO} + 0.2875 \text{Al}_2\text{O}_3 + 0.4626 \text{CaF}_2 + 0.2042$ \n$\text{MgO} + 0.0231 \text{CaO.Al}_2\text{O}_3 + 0.0521 \text{CaO.CaF}_2 + 0.0365 \text{CaO.MgO} - 0.0134$ \n$\text{Al}_2\text{O}_3.\text{CaF}_2 + 0.0140 \text{Al}_2\text{O}_3.\text{MgO} - 0.0163 \text{CaF}_2.\text{MgO}$ 

Impact strength $= -4.6949 \text{CaO} -0.8874 \text{Al}_2\text{O}_3-3.1084 \text{CaF}_2 -1.9637 \text{MgO} + 0.0484$ \n$\text{CaO.Al}_2\text{O}_3 + 0.2148 \text{CaO.CaF}_2 + 0.2447 \text{CaO.MgO} + 0.2145 \text{Al}_2\text{O}_3.\text{CaF}_2 + 0.1044$ \n$\text{Al}_2\text{O}_3.\text{MgO} + 0.0906 \text{CaF}_2.\text{MgO}$

Microhardness $= +3.3290 \text{CaO} +3.2701 \text{Al}_2\text{O}_3 +3.0573 \text{CaF}_2 +3.6445 \text{MgO}$ \n$-0.0424\text{CaO.Al}_2\text{O}_3 -0.0019 \text{CaO.CaF}_2 -0.0303 \text{CaO.MgO} -0.0104 \text{Al}_2\text{O}_3.\text{CaF}_2$ \n$-0.0162 \text{Al}_2\text{O}_3.\text{MgO} -0.0381 \text{CaF}_2.\text{MgO}$

- Individual effect of CaO (Calcium Oxide) flux constituent to flux mixture decrease ultimate tensile strength and percentage elongation of weld metal but binary mixtures of CaO with CaF2 (Fluorspar) and MgO (Magnesium Oxide) have a synergistic effect on weld metal ultimate tensile strength and percentage elongation.

- All individual constituents; CaO (Calcium Oxide), Al2O3 (Alumina), CaF2 (Fluorspar), MgO (Magnesium Oxide) tend to decrease impact strength but binary mixtures of these flux constituents have a synergistic effect on weld metal impact strength.

- Individual flux ingredient, Al2O3 (Alumina) in flux mixture tends to increase ultimate tensile strength (UTS) and decrease impact strength but binary mixture, Al2O3.CaF2 has a synergistic (increasing) effect on both UTS and impact strength.
• Individual flux ingredient, MgO (Magnesium Oxide) has increasing effect on UTS and microhardness at the centre of weld zone of weld metal but a decreasing effect on impact strength of weld metal.

• Individual flux ingredient, CaF$_2$ in flux mixture increases UTS and decreases impact strength but binary mixtures of CaF$_2$ with CaO (Calcium Oxide), Al$_2$O$_3$ (Alumina) and MgO (Magnesium Oxide) have synergistic effect on all mechanical properties; ultimate tensile strength, percentage elongation, impact strength and microhardness.

• The mathematical models for weld metal element content have been developed in terms of individual and binary flux mixtures. The developed models have been validated by conducting confirmatory experiments and mean percentage error for carbon, silicon, manganese, phosphorus and sulphur contents of weld metal are 7.0%, 6.2%, 5.2%, 5.9% and 5.5% respectively. The mathematical models for chemical composition of weld metal are as follows:

\[
C\text{ (WM)} = -0.00142\text{CaO} + 0.00181\text{Al}_2\text{O}_3 + 0.00277\text{CaF}_2 + 0.00349\text{MgO} \\
+ 0.00006\text{CaO.Al}_2\text{O}_3 + 0.00002\text{CaO.CaF}_2 + 0.00002\text{CaO.MgO} - 0.00012\text{Al}_2\text{O}_3\text{.CaF}_2 \\
- 0.00009\text{Al}_2\text{O}_3\text{.MgO} - 0.00014\text{CaF}_2\text{.MgO}
\]

\[
\text{Si (WM)} = + 0.00484\text{CaO} + 0.00645\text{Al}_2\text{O}_3 - 0.00225\text{CaF}_2 + 0.00107\text{MgO} \\
- 0.00026\text{CaO.Al}_2\text{O}_3 + 0.00001\text{CaO.CaF}_2 + 0.00008\text{CaO.MgO} + 0.00007\text{Al}_2\text{O}_3\text{.CaF}_2 \\
- 0.00019\text{Al}_2\text{O}_3\text{.MgO} + 0.00016\text{CaF}_2\text{.MgO}
\]

\[
\text{Mn (WM)} = + 0.03856\text{CaO} - 0.00047\text{Al}_2\text{O}_3 + 0.02478\text{CaF}_2 + 0.04196\text{MgO} \\
- 0.00016\text{CaO.Al}_2\text{O}_3 - 0.00026\text{CaO.CaF}_2 - 0.00148\text{CaO.MgO} + 0.00034\text{Al}_2\text{O}_3\text{.CaF}_2 + \\
0.00049\text{Al}_2\text{O}_3\text{.MgO} - 0.00108\text{CaF}_2\text{.MgO}
\]

\[
\text{P (WM)} = - 0.00037\text{CaO} + 0.00110\text{Al}_2\text{O}_3 - 0.00037\text{CaF}_2 + 0.00021\text{MgO} \\
0.00002\text{CaO.Al}_2\text{O}_3 + 0.00003\text{CaO.CaF}_2 + 0.00003\text{CaO.MgO} + 0.00000\text{Al}_2\text{O}_3\text{.CaF}_2 \\
- 0.00005\text{Al}_2\text{O}_3\text{.MgO} + 0.00001\text{CaF}_2\text{.MgO}
\]
\[
S\,(WM) = -0.00172CaO + 0.00025Al_2O_3 + 0.00113CaF_2 + 0.00016MgO + 0.00007CaO.Al_2O_3 + 0.00002CaO.CaF_2 + 0.00005CaO.MgO - 0.00005Al_2O_3.CaF_2 + 0.00000Al_2O_3.MgO - 0.00004CaF_2.MgO
\]

- Individual flux constituents; \(Al_2O_3, CaF_2\) and \(MgO\) in flux mixture tends to increase whereas binary mixtures; \(Al_2O_3.CaF_2, Al_2O_3.MgO, CaF_2.MgO\) tend to decrease carbon content of weld metal.

- Individual flux mixtures; \(CaO, CaF_2\) and \(MgO\) tends to increase weld metal manganese content whereas binary mixtures; \(CaO.MgO, Al_2O_3.MgO\) tend to decrease manganese content.

- Individual flux constituent; \(CaF_2\) is the most significant flux constituent and \(Al_2O_3\) is the second most significant flux constituent among individual mixtures.

- Binary mixture \(CaF_2-MgO\) is the most significant and binary mixture \(CaO-Al_2O_3\) is the second most significant binary mixture affecting weld metal content.

- Three solutions for flux mixtures have been provided, giving optimized weld metal mechanical properties and chemical content of weld metal equivalent to base metal for submerged arc welding of HSLA steel (API 5L X65). Optimum flux mixtures are as follows:

<table>
<thead>
<tr>
<th>No</th>
<th>CaO (%)</th>
<th>Al_2O_3 (%)</th>
<th>CaF_2 (%)</th>
<th>MgO (%)</th>
<th>UTS (MPa)</th>
<th>Impact strength (Nm)</th>
<th>Micro-hardness (VHN)</th>
<th>C (%)</th>
<th>Si (%)</th>
<th>Mn (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Desirability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.61</td>
<td>12.33</td>
<td>15.00</td>
<td>39.06</td>
<td>552.55</td>
<td>109.56</td>
<td>215.00</td>
<td>0.06</td>
<td>0.16</td>
<td>1.37</td>
<td>0.01</td>
<td>0.01</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>31.44</td>
<td>11.07</td>
<td>25.49</td>
<td>10.00</td>
<td>603.03</td>
<td>104.78</td>
<td>215.00</td>
<td>0.04</td>
<td>0.16</td>
<td>1.40</td>
<td>0.02</td>
<td>0.01</td>
<td>0.63</td>
</tr>
<tr>
<td>3</td>
<td>10.00</td>
<td>37.89</td>
<td>12.58</td>
<td>17.53</td>
<td>557.79</td>
<td>125.68</td>
<td>213.83</td>
<td>0.03</td>
<td>0.15</td>
<td>1.30</td>
<td>0.01</td>
<td>0.01</td>
<td>0.57</td>
</tr>
</tbody>
</table>

- Fine grained acicular ferrite content (AF) microstructure provided highest ultimate tensile strength in weld metal as concluded from microstructural analysis.

- Presence of gas holes (GH) and foreign particles (FP) in the weld metal retarded the mechanical properties of the weld metal.
Silicates and silicate hydroxides compounds were observed through XRD analysis of slag samples in most of the high basicity slags and lesser in low basicity slags.

6.2. Scope for Future Work

- The effect of welding parameters and flux constituents on the heat-affected zone (HAZ) could also be studied to get a clearer picture of the properties in this zone; and correlated correspondingly to the flux constituents.
- Slag samples may be analyzed through EDX for chemical analysis which may be further utilized for complete chemical analysis of base metal, flux mixture, electrode wire, weld metal and slag.
- The methodology used in the work may be applied to other grades of structural steels for designing and developing of fluxes.
- Flux development technique may be applied to enhance wear resistance in applications such as hard surfacing using submerged arc welding.
- Two wire tandem submerged arc welding is also a major thrust area for the related research work.