CHAPTER 1

INTRODUCTION

1.1 CLADDING

Surfacing is a process of depositing a filler metal on a base metal to impart some desired property to the surface with respect to the underlying base metal. There are four types of surfacing namely hardfacing, build up, cladding, and buttering. Hardfacing is a form of surfacing that is applied for the purpose of reducing wear, abrasion, impact, erosion, galling and cavitation. Build up refers to the addition of weld metal to a base metal surface for the restoration of the component to the required dimensions. Cladding is a relatively thick layer of filler metal applied to a carbon or low alloy steel base metal for the purpose of providing a corrosion-resistant surface. Buttering involves the addition of one or more layers of weld metal to the face of the surface to be welded to satisfy some metallurgical consideration. It is used primarily for the joining of dissimilar base metals.

The process of surfacing appears to have been developed initially for the needs of oil-well drilling industry but is now widely used for the fabrication of engineering components that are used in chemical, fertiliser, nuclear power plants, food processing, petrochemical and their allied industries, agricultural machines and even in aircraft and missile components. The primary objective of surfacing is to impart desirable properties to the surface of a substrate to conserve expensive or difficult-to-obtain materials by coating the same with a material possessing desired properties. This results in considerable economic gains.
1.2 WELDING PROCESSES EMPLOYED FOR CLADDING

A wide range of fusion welding processes along with their variants and their characteristics as listed in Table 1.1 may be employed for cladding. The selection of an optimum welding process with suitable technique for a specific application is made on the basis of the following considerations:

- Size and shape of the component
- Chemical composition of the deposit
- Metallurgical effect on parent material properties
- Surface finish and distortion
- Operating economics

**TABLE 1.1 Welding processes and their characteristics (Ref: www.azom.com)**

<table>
<thead>
<tr>
<th>Welding process</th>
<th>Variants available</th>
<th>Typical deposit thickness, mm</th>
<th>Deposition rate</th>
<th>Parent metal dilution, %</th>
<th>Operational features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy-fuel Gas Welding</td>
<td>Rod</td>
<td>1.0-2.0</td>
<td>Low</td>
<td>15-20</td>
<td>Low cost and versatile.</td>
</tr>
<tr>
<td></td>
<td>Powder</td>
<td>0.5-1.0</td>
<td>Low</td>
<td>12-15</td>
<td>Low dilution and thin layers.</td>
</tr>
<tr>
<td>Manual Metal Arc Welding</td>
<td>Rod</td>
<td>3.0</td>
<td>Low</td>
<td>20-25</td>
<td>Versatile, all positions but manual only.</td>
</tr>
<tr>
<td>Gas Tungsten Arc Welding</td>
<td>Rod/wire</td>
<td>1.5-2.0</td>
<td>Low</td>
<td>15-20</td>
<td>Torch to work piece distance to be held to within close tolerances.</td>
</tr>
<tr>
<td></td>
<td>Hot wire</td>
<td>3.0-4.0</td>
<td>Moderate</td>
<td>10-15</td>
<td>Increased deposition rate.</td>
</tr>
<tr>
<td>Welding process</td>
<td>Variants available</td>
<td>Typical deposit thickness, mm</td>
<td>Deposition rate</td>
<td>Parent metal dilution, %</td>
<td>Operational features</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------</td>
<td>-------------------------------</td>
<td>----------------</td>
<td>-------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Plasma Transferred Arc Welding</td>
<td>Powder</td>
<td>0.5-2.0</td>
<td>Low</td>
<td>8-10</td>
<td>Wide range of thickness.</td>
</tr>
<tr>
<td></td>
<td>Hot wire</td>
<td>3.0-4.0</td>
<td>Moderate</td>
<td>10-12</td>
<td>Less sensitive than GTAW.</td>
</tr>
<tr>
<td></td>
<td>Two wires</td>
<td>4.0-5.0</td>
<td>High</td>
<td>10-12</td>
<td>High deposition rates with low dilution.</td>
</tr>
<tr>
<td>Gas Metal Arc Welding (GMAW)</td>
<td>Solid wire</td>
<td>Pulsed</td>
<td>2.0-3.0</td>
<td>Low</td>
<td>15-18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spray</td>
<td>4.0-6.0</td>
<td>Moderate</td>
<td>12-15</td>
</tr>
<tr>
<td></td>
<td>Flux cored</td>
<td>Single wire</td>
<td>2.0-3.0</td>
<td>Moderate</td>
<td>12-15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 wires</td>
<td>4.0-6.0</td>
<td>High</td>
<td>12-18</td>
</tr>
<tr>
<td>Submerged Arc Welding</td>
<td>Single wire</td>
<td>3.0-5.0</td>
<td>Moderate</td>
<td>25-30</td>
<td>Flux composition controls deposit chemistry.</td>
</tr>
<tr>
<td></td>
<td>Multi wire</td>
<td>6.0-7.0</td>
<td>High</td>
<td>20-25</td>
<td>Parallel wires to broaden the deposits.</td>
</tr>
<tr>
<td></td>
<td>Strip electrode</td>
<td>4.0-5.0</td>
<td>High</td>
<td>20-25</td>
<td>High deposition rates without increasing dilution.</td>
</tr>
<tr>
<td>Electro slag Welding</td>
<td>Strip electrode</td>
<td>4.0-6.0</td>
<td>High</td>
<td>15-20</td>
<td>High deposition rates, lower dilution than submerged arc welding</td>
</tr>
</tbody>
</table>
1.3 CLADDING BY PLASMA TRANSFERRED ARC WELDING (PTAW)

Among the fusion welding processes employed for cladding, the plasma transferred arc welding (PTAW) has become popular and is accepted by the industries due to the following features:

- Lower dilution of the base metal with high deposition rates
- Improved economy
- Enhanced quality
- Increased productivity
- Ease and accurate control of process parameters
- Amenable for automation

Plasma transferred arc (PTA) welding is an electric arc welding process that uses a constricted arc between a non-consumable tungsten electrode and the weld pool or between the electrode and the constricting nozzle. A conventional DC power supply connected between the tungsten electrode and work provides the energy for the main or transferred arc in PTAW. In PTA hard facing, metal powder is carried from the powder feeder to the electrode holder in an arc gas stream. From the torch the powder is directed into the arc effluent, where it is melted and fusion bonded to the base metal. Argon is provided as a blanket of shielding gas in the arc zone.

Deposits produced by PTAW are homogeneous and are fusion bonded to the work piece. The heat distribution afforded by the constricted arc coupled with the buffering action of the powder results in overlays having dilution values approaching much lower than those obtained with the TIG process. Under certain conditions, deposition rates approach those of the
submerged arc process with less than 10% dilution. The plasma arc weld surfacing process produces smooth deposits of controlled thickness usually resulting in reduced material and finishing costs. PTAW is the most suitable process for the application of chromium and Nickel based alloys. It finds extensive use in applications such as valve industries, Hydraulic machineries, Mining industries, Earth moving equipment, Chemical, Nuclear and Thermal power plants etc.

1.4 NEED FOR THE STUDY

Austenitic stainless steels are characterised by their high strength, excellent toughness, good corrosion resistance combined with resistance to stress corrosion cracking and corrosion fatigue. The chromium and molybdenum present in the austenitic stainless steel enhances their resistance to corrosion. Austenitic stainless steel offers several advantages over other category of stainless steels. The bead formation and dimensions are strongly affected by primary parameters such as welding current, torch travel speed, powder feed rate, oscillation frequency, torch standoff distance, shielding gas flow rate, powder gas flow rate, etc. Though considerable amount of work has been done in this area in predicting the effects of process parameters on weld bead geometry, few works have been reported in the development of regression models using the Response Surface Methodology (RSM), for precisely predicting the same for austenitic stainless steel AISI 316L cladding deposited by PTAW process. Hence, it was decided to carry out this research work.

Corrosion is a major problem in chemical, fertiliser, petrochemical and allied industries. A huge quantity of metal is lost by corrosion, which affects the environment as well as the cost of products. The development of new chemical technologies which require storage facility for more corrosive substances creates a demand for newer materials for the fabrication of larger
storage and pressure vessels. The cost is however, an important criterion. The fabrication of a vessel entirely from a corrosion resistant material becomes an extremely uneconomical solution in many situations. The composite materials solved these problems, using a base material of carbon or low-alloy steel providing the strength of the structure and a clad layer of corrosion-resistant material in contact with the corrosive atmosphere. The clad layer is generally obtained by rolling, explosive welding and fusion welding processes. Of all these processes, the fusion welding by PTAW is readily accepted by the industries due to its lower dilution and versatile application combined with automation and safety.

Wear is the result of impact, erosion, metal to metal contact, abrasion, oxidation and corrosion, or a combination of these. The effects of wear can be repaired by welding. Surfacing with special welding filler metals is used to replace worn metal. Hard facing is used to apply a coating to reduce wear. It can be used to extend the usable life of wear parts. It will save money since the replacement of worn parts is costly, particularly when the downtime and repair labour is considered. To select the proper hard facing alloy, it is necessary to understand the type and mechanism of wear that caused the metal to degrade. The type of wear can be impact wear, abrasive wear, erosion, cavitation, metal to metal contact wear, corrosion wear and oxidation. Many of these types of wear occur in combination. It is wise to look for a combination of factors that create the wear problem in order to determine the type of surfacing material to apply.

1.5 THESIS OBJECTIVES

The objectives of the thesis are focussed on the investigations that are carried out on cladding of AISI 316L austenitic stainless steel powder over low carbon steel substrate by the PTAW process. The main objectives of the present research work are given below:
- To establish an operating window for AISI 316L austenitic stainless steel cladding of low carbon steel by PTA welding process.
- To develop regression models using the RSM to predict the effect of the PTA cladding process parameters on the clad bead geometry.
- To optimise the PTAW process parameters to obtain lower dilution in the cladding.
- To study direct and interaction effects of PTAW cladding process parameters on the clad bead geometry.
- To estimate the residual stresses developed during stainless steel cladding of carbon steel plate at different heat input and with optimum heat input conditions using the X-ray diffraction method.
- To improve the corrosion wear properties of the surface of the cladding by developing a unique and novel surface modification process called low temperature liquid nitriding.
- To optimise the process parameters of liquid nitriding to improve their surface properties.
- To evaluate the mechanical behaviour of the stainless steel claddings to confirm the plastic properties of the clad layer through bend testing.
- To estimate and compare the wear behaviour of the claddings deposited at different heat inputs and at optimum dilution conditions in the as cladded and nitrided conditions.
- To identify the susceptibility of the cladding towards pitting and intergranular corrosion that are deposited at different heat
inputs viz. low, medium and high heat inputs and also with optimum dilution condition in the as cladded and nitrided conditions, by conducting Electrochemical Potentiokinetic Reactivation (EPR) and Weight loss tests.

- To study microstructure and microhardness variations and to measure the delta ferrite content of the cladding deposited at different heat inputs and at optimum dilution conditions in the as cladded and nitrided conditions.

### 1.6 PLAN OF INVESTIGATIONS

The present research work was carried out to investigate the effects of PTAW process parameters on the clad bead geometry of stainless steel claddings. The PTAW process parameters that were considered for the present investigation were welding current, torch travel speed, powder feed rate, oscillation frequency and torch standoff distance. The base metal used in this investigation is structural steel (AISI 1040 / IS: 2062), a versatile material used in industrial fabrications. The clad metal used is the low carbon austenitic stainless steel of grade AISI 316L (UNS 316 03), popularly called as the marine grade stainless steel applied widely in the fabrication of pressure vessel parts, nuclear reactor components and also in the fabrication of piles in offshore applications. Some of the important aspects of the present research work are detailed under the following headings.

#### 1.6.1 Prediction of clad bead geometry

The clad bead parameters such as clad bead width (W), depth of penetration (P), height of reinforcement (R), and percentage dilution (D) as shown in Figure 1.1 greatly influence mechanical and metallurgical characteristics of the deposit.
Central composite rotatable design was selected to conduct the experiment. To study the main and interaction effects of process parameters on clad bead geometry, regression models were developed using multiple regression method. The developed regression models were checked for their adequacy and significance. The models developed could be used to predict the clad bead geometry by substituting the coded values of the respective process parameters.

1.6.2 Cladding process optimisation to reduce weld dilution

Dilution value between 7% and 10% in the claddings is generally considered to be optimum (Marimuthu and Murugan, 2003). Dilution less than 7% decreases the bond integrity and greater than 12% increases the cost of the filler material and reduce the corrosion and wear resistance properties (Balasubramanian et al, 2008). Hence, optimisation of the cladding process parameters to obtain optimum dilution is very essential. In this study, an optimum dilution of 10.3% was obtained by using the optimisation toolbox available in the solver module of Microsoft Excel.
1.6.3 **Estimation of the residual stresses developed in stainless steel claddings**

Residual stress is the stress that exists within a material without application of an external load (Withers and Bhadeshia, 2000). In many cases, unexpected failures were occurred due to the presence of residual stresses which seriously shortened component life. Claddings at different heat input conditions were produced. The residual stresses present in the claddings were measured using X-ray diffraction method.

1.6.4 **Liquid nitriding**

Liquid nitriding is a ferritic thermo chemical heat treatment carried out below the eutectoid temperature of 600°C (that is, below the critical transformation temperature) of Fe-N system (Larisch et al 1999, Minak and Ceschini 2008). It was carried out at temperatures between 550°C and 580°C for 2 hours. Hence components being liquid nitrided are subjected to minimum distortion combined with improved corrosion and wear resistance. The conventional liquid nitriding processes are based on cyanide-carbonate baths which are highly toxic and requiring elaborate precautions for human safety and effluent disposal (Ceschini and Minak 2008, Fernandez et al 2008). The growing environmental awareness, coupled with the ever increasing cost of detoxification of effluents has created the necessity for a non-toxic equivalent of these processes. In the present investigation, the nitriding bath consisted of a base salt containing only cyanate and carbonate salts of lithium, sodium and potassium, thereby making the process neither pollutive nor toxic. Also, the liquidnitriding process parameters were suitably optimised to obtain maximum thickness of the nitride layer. Also, the hardness depth profile of the liquid nitrided claddings was also measured and investigated.
1.6.5 Estimation of soundness and wear properties of stainless steel claddings

Claddings are often tested for soundness, strength and toughness by means of mechanical tests, which are destructive in nature. The quality of the clad, in terms of ductility of the clad metal and HAZ as well as the presence of defects particularly lack of fusion, are most frequently checked by means of a bend test. The 180° side bend and face bend tests were carried out according to ASTM A-264 procedures to check the ductility of the claddings and to analyse the influence of welding process parameters and welding conditions on the plastic properties of the clad layer and joining between base metal and clad layer. To evaluate and compare the wear behaviour of the as cladded and nitrided claddings produced at different heat input and optimum dilution conditions the wear test was conducted as per ASTM G-99 procedures.

1.6.6 Corrosion studies

The stainless steel cladding must resist several types of corrosion such as pitting corrosion and intergranular corrosion (Giridharan and Murugan, 2007). Pitting corrosion refers to the formation of microscopic holes on the surface of metals or alloys either due to direct corrosion of heterogeneities present on the surface or due to the localised damage caused to the protective passive film present on the surface. It is well known that pitting corrosion occurs on passivated surface that are protected by a thin self-healing, tenacious and a stable oxide layer. Under the influence of aggressive anions such as halides, localised attack takes place on the passivated surface causing the formation of hemispherical and other shapes of polygonal holes called pits. Pitting corrosion studies of the claddings were carried out using potentiodynamic anodic polarisation technique as per ASTM-G-5 procedure.
The results were compared with the total immersion ferric chloride test which was carried out as per ASTM-G-48 procedure.

Also, the chromium and carbon content present in the stainless steel combine together to form a continuous network along the grain boundaries when heated 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. This phenomenon is known as intergranular corrosion or sensitization or weld decay (Kamatchimudali and Dayal 2000). For investigating the susceptibility to inter granular corrosion of the stainless steel claddings, the Double loop EPR test was carried out and the results were compared with the boiling nitric acid or the Huey’s test which was carried out as per ASTM-A-263-Practice-C.

1.6.7 Studies on metallurgical Characterisation

The quality of the claddings primarily depends upon the hardness of the interface which is primarily governed by the heat input. The mechanical and corrosion resistance properties of cladding are directly related to the clad microstructure. Hence, careful and comprehensive studies of the microstructure of the claddings for achieving quality claddings are essential. This comprehensive study includes microhardness survey, measurement of delta ferrite content and metallographic studies and they are explained below.

1.6.7.1 Microhardness survey

The microhardness measurements on the claddings in the as cladded and nitrided condition were carried out. The microhardness was measured along the cross section of the specimen encompassing the base metal, HAZ, fusion line and overlay. They are presented in the graphical form and are discussed appropriately.
1.6.7.2 Studies on delta ferrite content in stainless steel claddings

Stainless steel claddings contain delta ferrite, which is expressed in terms of Ferrite Number (FN). The weld metal ferrite content can influence a wide range of properties, including corrosion resistance, toughness, long term high temperature stability, resistance to hot cracking etc. The amount of ferrite present in the deposit is a function of chemical composition of the filler and the base metals, welding process, type of shielding gas, welding procedure, and heat input during cladding. Excessive ferrite can result in poor resistance to corrosion resistance. Likewise, insufficient ferrite can also produce inferior mechanical and corrosion resistance properties. Hence, the amount of ferrite is essential to obtain the required mechanical and corrosion resistant properties. The ferrite number was measured by the feritescope as per the ASTM standards in the claddings in as cladded and nitrided conditions.

1.6.7.3 Metallographic studies

Both corrosion and mechanical properties of austenitic stainless steel cladding depends very much on the microstructure of the claddings. Metallographic techniques were used to study the microstructure of the base metal, HAZ, fusion line and clad layer. The microstructures of as cladded and liquid nitrided claddings produced at low, medium, and high heat input and optimum dilution conditions were studied with the help of an optical microscope. Microstructures were observed at different magnifications in different regions of the base metal and the cladding.

1.7 SEQUENCE OF INVESTIGATIONS

To accomplish the objectives of the present research work, detailed investigations were carried out. The plan of the investigations is presented in Figure 1.2 and the sequence of investigations is presented in Figure 1.3. Initial trial runs were conducted to find out the upper and lower limits of the cladding process parameters. Experiments were conducted as per the chosen
design matrix and the bead geometry was measured. Regression models were
developed using RSM to predict the effect of cladding process parameters
over the clad bead geometry. Optimisation of the process parameters was
done using the developed models with the help of Excel Solver to find the
optimum weld dilution and the cladding was carried out with the optimised
process parameters. A unique and novel surface modification process called
low temperature liquid nitriding was developed for the specimens cladded at
various heat inputs and also at optimum cladded conditions to improve the
corrosion and wear properties of the stainless steel claddings.
Figure 1.2 Plan of investigations

- Literature survey
- Procurement of substrate, SS metal powder and shielding gas
- Conducting trial runs
- Design of experiments and conducting experiments
- Measurement of clad bead geometry and development of regression models
- Optimisation of cladding process parameters and cladding at optimum condition
- Estimation of the Residual stresses developed in claddings produced at different heat input and at optimum conditions
- Low temperature liquid nitriding (LN) and Optimisation of LN process parameters
- Mechanical and metallurgical characterisation of stainless steel cladding at as cladded and nitrided specimens
- Evaluation of Pitting and Intergranular corrosion susceptibility (EPR and Weight loss) of claddings as per ASTM standards at as cladded and nitrided conditions
- Conclusions
Figure 1.3 Sequence of investigations
The side and root bend tests are carried out for the claddings to analyse the influence of welding process parameters and welding conditions on the soundness of the clad layer, the wear test was conducted using a pin on disc wear testing machine to identify and compare the wear behaviour of the samples cladded at different heat input conditions and at optimum dilution condition in the as cladded and nitrided conditions. Detailed metallurgical investigations such as microhardness survey, microstructure studies and measurement of Ferrite number were carried out. Finally, the susceptibility of the SS claddings in the as cladded and nitrided conditions towards pitting and intergranular corrosion resistance were investigated using EPR and acid immersion tests based on weight loss methods, as per ASTM procedures.

1.8 THESIS ORGANISATION

Based on the above sequence of investigations, different chapters in this thesis are incorporated in the following sequence:

- **Chapter II** presents the literature survey related to the prediction of the clad bead geometry, optimisation of the cladding process parameters, low temperature liquid nitriding, shear and bend testing, metallurgical transformations, studies on measurement of ferrite number, microstructural analysis, studies on the susceptibility of the cladding towards pitting and intergranular corrosion and also their wear resistance.

- **Chapter III** describes the experimental procedures and development of regression models to predict clad bead geometry along with the analysis of the direct and interaction effects of the cladding process parameters on clad bead geometry. Also, the optimisation of the developed models are carried out to find the optimum dilution conditions.
• **Chapter IV** deals with the estimation of the residual stresses that are developed during stainless steel cladding under different heat input and at optimum dilution of claddings is presented.

• **Chapter V** deals with the development of a novel surface modification method called the low temperature liquid nitriding for stainless steel to improve the corrosion and wear resistance of the stainless steel claddings deposited at different heat inputs and at optimum dilution conditions in the as cladded and nitrided conditions.

• **Chapter VI** presents the tests to confirm the soundness of the cladding by conducting side and root bend tests as per ASTM procedures. Also, to identify and compare the wear behaviour of the claddings produced at different heat inputs and at optimum dilution condition in the as cladded and nitrided conditions, the wear test was conducted by using pin on disc wear testing machine.

• **Chapter VII** illustrates the studies concerned with the susceptibility of the claddings in the as cladded and nitrided conditions towards pitting and intergranular corrosion resistance by conducting EPR and weight loss tests as per ASTM procedures.

• **Chapter VIII** deals with the detailed metallurgical investigations on the microhardness survey, measurement of ferrite number and microstructural studies of the claddings in the as cladded and nitrided conditions.

• **Chapter IX** provides the conclusions of all phases of the investigations and the scope for further work.