CHAPTER -1
INTRODUCTION

1.1 INTRODUCTION

Stainless steels are versatile engineering materials meeting a broad range of design criteria. They are preferred over many other materials due to their excellent corrosion resistance, strength at elevated temperature, toughness at cryogenic temperature and easy fabrication characteristics. Arc welding process is commonly used for fabrication of stainless steel products, components or equipments. Austenitic stainless steels are easily weldable material. A stainless welded joint should have good weld bead profile, better corrosion resistance, and strength as equal to or slightly more than that of base metal. However, fabricators should recognize that any metal including stainless steel may undergo change in metallurgical and mechanical properties during welding as it involves sudden cooling of weld metal from melting point to room temperature in a very short period of time.

There are number of welding process and material considerations which are important for the production of sound austenitic stainless steel weld. Some of the important considerations are solidification cracking, variable penetration in autogenous welding, loss of corrosion properties, distortion, melt through, warpage etc. Although austenitic stainless steels are predominantly austenitic, they often contain small amount of ferrite phase having BCC structure, particularly in weld metal. This ferrite is often referred to as delta ferrite since it forms at elevated temperature and is distinguished from alpha ferrite, which is the low temperature phase in iron base alloys. For a given composition of stainless steel, delta ferrite may be present in various amounts and in different morphologies within the weld metal depending upon the solidification mode and the rate of cooling of molten weld pool to room temperature [1]. Its content and morphology affect both hot cracking and corrosion properties of stainless steel. So weld metal of austenitic stainless steel is generally designed to contain 3 -12 % of delta ferrite in final microstructure in order to increase the resistance to solidification cracking and to prevent loss of corrosion resistance properties. These conditions again depend on the type of welding process and welding process variables used in addition to chemical composition. Therefore, it is necessary to exercise a reasonable degree of care to minimize or to prevent any deleterious effect that may occur during the welding and
preserve the same degree of corrosion resistance and other properties of the weld zone as in the base metal. Since stainless steels are more expensive than regular steel and have problems in welding like variation in penetration (cast to cast variation), melt-through, warpage, solidification cracking, loss of corrosion properties especially for thin stainless steel sheets, it has become necessary to choose the optimum process parameters so as to obtain the weld free from above defects.

Among the various arc welding processes available, Gas Tungsten Arc Welding (GTAW) process is the most commonly and extensively used in industries for welding of thin stainless steel sheets. It can produce high quality and clean welds. Pulsed Current GTAW (Pulsed GTAW) process was introduced in late 1960s as a variant of continuous current GTAW. The pulsed GTAW process has many specific advantages over Continuous Current GTAW, such as enhanced arc stability, increased weld depth/width ratio, narrower Heat Affected Zone (HAZ) range, reduced hot cracking sensitivity, refined grain size, and reduced porosity. It was therefore, decided to use pulsed GTAW Process for welding of thin stainless steel sheets for the present investigations.

1.2 HISTORY OF PULSED GTAW WELDING PROCESS

The theoretical development of gas shielded arc welding was begun approximately in 1890. A patent was granted for the idea of surrounding a bare electrode with a carbon dioxide gas shield. This idea eventually led to the atomic hydrogen arc welding process, which is the basis for the inert gas arc welding process of today. Henry M. Robert and Philip K. Bevers were granted patents in 1930 for the arc welding of metals with high melting temperature tungsten, or carbon electrodes without any flux in an inert atmosphere of either Helium or Argon. However, in 1940, Russell Meredith developed the inert gases shielded arc welding process for the welding of Aluminum and Magnesium based alloys used for airplanes. The first helium inert gas shielded arc welding process having electrode holder with a tube extending upto the tip of the tungsten electrode was used and the process was called Heliarc. From this basic process, GTAW and Gas Metal Arc Welding (GMAW) processes were evolved [2].

Tungsten arc welding has been known from time it was first developed in USA in the early 1940 for the welding of Magnesium and Aluminum alloys using AC power source. In spite of its versatility, its use was largely confined to special applications requiring more precision and control of the weld joint than that of conventional Shielded
Metal Arc Welding consumable electrode processes. Even now GTAW welding process being a special arc welding process, although outwardly, it is one of the simplest welding process [3].

The GTAW welding process is well suited for welding thin sheets, foil of all weldable metals, root pass welding and welding of reactive and refractory metals such as Magnesium and Aluminum alloys. However, the problem of hot cracking in chromium-nickel and chromium-nickel-molybdenum containing austenitic stainless steels and nickel based refractory alloys during welding cannot be solved satisfactorily using GTAW process. In the longitudinal welding of small diameter tubes required for geometric reasons, single sided welding on the tube in nuclear technology is difficult to do it. In all these cases, continuous current GTAW does not always ensure the required joint quality with consistency but by using pulsed GTAW process, it is possible to solve the above problems [2].

Pulsed GTAW was first described some twenty years later, in 1960's mainly in Russian technical literature. In pulsed GTAW process, welding current is pulsed between high and low level at short or long time interval so that it brings zones of weld to the melting point during the peak pulse current and to allow this weld pool to cool and solidify during the low background current period. The weld bead shape will be of series of overlapping weld spots and the amount of overlap depends upon the pulse frequency and the welding speed [2]. This process is well suitable for joining thin and medium thickness materials like stainless steels and for applications where metallurgical control is critical. The beneficial effects of the process are low heat input, low distortion, controlled bead volume, less hot cracking tendency, less absorption of gas by weld pool, better control of the fusion zone and therefore improved behavior on badly prepared joint, reduction on HAZ etc. These advantages have influenced many stainless steel fabricating industries to use pulsed GTAW process for welding of thin stainless steel. The major applications of pulsed GTAW process are to control the penetration in thin sheet welding, the root pass welding of thicker plate and for controlled penetration in an edge weld. Further more pulsed GTAW is also used for making joint where there is disparity in heat sink due to differences in material thickness or due to a difference in thermal conductivity as in the joining of sheet to mesh and dissimilar metal welding [3].

However, in spite of the fact that pulsed GTAW process has many advantages over Continuous Current GTAW process, it has not become very popular due to lack of
awareness of its advantages and lack of confidence of welders towards working with pulse current parameters during welding. Total advantages of this process can only be brought about by a detail study on the process parameters and its optimizations through developing mathematical model. So pulsed GTAW process parameters have to be optimized for application in mechanized or automatic welding of stainless steel. Hence, importance of pulse current process parameters for welding of stainless steel sheets have to be studied in detail with regard to weld bead geometry, metallurgical characteristics, mechanical and corrosion resistance properties.

1.3 DEFINITION OF THE PROBLEM
The ever-increasing demand for high precision and high production rates leads to the development of fully mechanized or automated welding processes. The rate at which automation is being introduced into welding fabrication is astonishing and at the end of this decade it may not be uncommon to see automated machines replacing manually operated machines in the fabrication units. Automated and mechanized GTAW can lead to the problem of ensuring that the required weld bead profile and penetration are achieved consistently. The variations in weld bead penetration can be caused by number of process or material factors, including variation in component dimensions, joint fit-up, welding parameters and material composition [4]. To make the effective use of automated system, it is essential that a high degree of confidence to be achieved in predicting the weld bead geometry for the desired weld bead quality. This can be easily achieved with the help of statistically designed experiments, the development of mathematical models and the optimization of models.

As there is little published data available for welding of stainless steel sheets by pulsed GTA welding process, it was decided to investigate into the above aspect of the problem with more emphasis on the development of mathematical models and optimization for achieving a sound weld with qualities equal to or better than those of base metal, allowing for any metallurgical change that can take place during welding. However, a thorough understanding of process characteristics affecting the technological and metallurgical characteristics of the weld will assist in achieving better weld bead quality. Hence, to establish a better procedure, it is essential to study the main and the interaction effects of various process parameters affecting the weld bead dimensions. From the literature survey made, it was observed that though extensive work has been
carried out to investigate the effects of process parameters on weld characteristics, not much efforts have been put to develop mathematical models to predict the same. The present investigations were therefore undertaken with a view to generate adequate data for the following aspects of autogenous welding of thin austenitic stainless steel sheets by pulsed GTAW process with the main aim of effectively controlling the depth of penetration and bead geometry: The following studies were carried out in the order as mentioned below:

- Development of mathematical model for predicting the effects of process parameters on bead dimensions.
- Selection of suitable process parameters for obtaining desired weld bead geometry by optimization and sensitivity analysis.
- Study of delta ferrite contents and its morphology and to correlate them with process parameters.
- Study of metallurgical transformation in weld metal including modes of solidification and
- Study on corrosion resistance parameters of the weld by conducting electrochemical corrosion tests for pitting corrosion and intergranular corrosion.

1.4 PLAN OF RESEARCH
The research work, presented in the following chapters of this thesis, was undertaken to investigate the effect of different process variables of pulsed GTAW on weld bead geometry in welding of thin stainless steel sheets. The important process parameters were selected based on trail runs and they were pulse current, pulse current duration and welding speed for obtaining full penetration weld. Various aspect of planned research work is presented in Fig.1.1. An introduction to all aspects with a resume of the work done by others in these directions is detailed under the appropriate heading as follows.

1.4.1 PREDICTION OF WELD BEAD GEOMETRY
The study of weld bead geometry includes measurements of penetration, bead width and weld bead area. Bead geometry is very important as it determines the technological and metallurgical characteristics of the weld bead [5 -7]. Bead dimensions are also affected by the change in pulsed GTAW process primary parameters such as pulse current, pulse...
current duration, welding speed and secondary parameters like arc length, electrode tip angle and types of fit-up. Also, with the increased emphasis on the use of automated and robotic applications, such a study is necessary for accurate means of selecting process parameters, welding procedures and to predict weld bead shapes and dimensions. The present study will help to obtain a sound weld at an economical rate in welding of thin austenitic stainless steel sheets (304L) and establishing a standard procedure to predict and control weld bead geometry for pulsed GTAW process.

1.4.2 DEVELOPMENT OF MATHEMATICAL MODEL

It is essential to ensure that adequate weld bead quality with desired mechanical and corrosion resistance are obtained with high degree of confidence for effective utilization of the process. This can be achieved only when the process parameter were thoroughly studied and controlled. Though considerable amount of work has been done in this area [8-12] for studying the effects of process parameters on bead geometry, very limited work has been done to develop mathematical models for precisely predicting the same. It was therefore, considered relevant to undertake this aspect of study of developing mathematical models to enable the end user to make use of these models without wasting time in carrying out the trial runs for optimizing the welding parameters.

To study the above aspects, the investigations were carried out in two phases. In first phase, a large number of trial runs were made to determine the ranges of useful process parameters such as pulse current, pulse current duration, welding speed keeping other parameters constant so as to obtain full penetration. These values were made use of in designing the experiments based on central composite design matrix of five level three factors full factorial technique [5]. Experiments were conducted as per the design matrix. In second phase, the main and the interaction effects of process parameters, I, I_p and S on depth of penetration, weld bead width and weld bead area were studied. The welded sheets were cross sectioned at their mid section to obtain test specimen of 15 mm width. The weld specimens were polished by the usual metallurgical methods and electrolytically etched with 10 % oxalic acid. The weld profiles were traced using a reflective type optical profile projector for weld area measurements and the bead dimensions were measured with the help of digital planimeter of 0.001mm accuracy. Using these response values, mathematical models were developed by employing regression analysis and their adequacies were tested by analysis of variance (ANOVA) method. The regression
coefficients obtained were checked for their significance by using the student’s t-test and the less significant coefficients were dropped from the mathematical models without losing accuracies of the models [6].

The developed models as explained above could be effectively used for predicting the bead shape and dimensions more accurately within the working region of the process parameters. The response parameters can be predicted by substituting the values of the process parameters in the equations. The main and the interaction effects of various parameters on the bead geometry can be estimated from the mathematical models. Also the selection of suitable process parameters, i.e., the procedure, to achieve minimum weld bead area and maximum penetration can be established with the help of these models. The scatter diagram was employed to check the correlation between predicted and observed values. The results obtained were quite satisfactory, and a few of them are presented in chapter IV.

To check the precision of the results predicted by the models, conformity tests runs were conducted by assigning some intermediate values (not covered in design matrix) within the working region of the process variables and the weld bead parameters were measured.

1.4.3 OPTIMIZATION OF THE BEAD PARAMETERS.
One of the common problems that often faced in the fabrication industry is the optimization of the bead parameters or to find the optimum values of the process variables to obtain desirable weld bead [12, 13]. Also welding is done with the aim of achieving sound and defect free joints at lower cost. But without optimization, it is impossible to achieve the above aims. So the optimization of the weld bead was carried out in the present study. The optimization process is iterative, requiring the same set of calculations repeated several times [14]. Till the recent past, cost and time intensive trial and error methods were used to determine the optimum process parameters for a required bead quality since any welding process is a multi objective problem (maximum penetration, minimum bead width and minimum total weld bead area). The optimum solution is a compromise [15] between each objective. Selection of appropriate weld bead parameters is also equally important because if the selected parameters are the one whose value is determined and controlled by most of the other important bead parameters, then the optimization of those parameters will obviously include all other parameters. Total weld
bead area is such an important bead parameter whose dimensions are controlled by the 
most of the other bead parameters. Hence, if the total weld bead area is minimized, 
obviously cost will also be minimized.

The limits of the constraints equation (bead parameters) were taken based on the 
general requirement of weld bead such as minimization of the size of the weld bead 
reducing the welding cost through reduced heat input and energy consumption and 
increased welding output rate for the same welding facilities by having high welding 
speed, but for a sound and strong weld metal should have full penetration [16]. So far no 
work has been done in this aspect for pulsed GTAW process. Hence, it was decided to 
minimize the total bead area with other important bead parameters as the constraint to 
obtain optimum weld bead qualities [17, 18]. The optimization was carried out using the 
MATLAB software version 5.3

To check the results of optimization, conformity test runs were conducted with the same 
experimental set up. The process parameters were assigned the values (in their natural 
scale) as close as possible to the optimum values (selected from the results of the 
optimization process) after confirming their availability in the process parameters setting 
range of the equipment. The results of conformity test were recorded. A comparative 
study between the observed (results of conformity test) and predicted (results of 
optimization) results were made and the percentage of error was calculated and presented 
in chapter IV.

1.4.4 METALLURGICAL STUDIES

The properties of the austenitic stainless steel weld metal are strongly influenced by its 
microstructure containing delta ferrite and its morphology. Susceptibility to hot cracking, 
low temperature toughness and corrosion resistance properties are strongly influenced by 
the complex austenitic-ferrite structures, which may develop depending on steel chemical 
composition and cooling rate. It is very important to understand the solidification mode 
and sequence. The possible primary solidification modes and subsequent solid state 
transformations were studied in order to correlate the microstructure of the weld metal 
with the pulse GTA welding process parameters on the one hand and the properties of the 
welded joints on the other. As the microstructure is the results of thermal cycle involved 
and it governs the performance of the welded joint, a detailed survey of microstructures 
and macrostructures were carried out.
Standard metallographic technique was used to reveal the microstructure in the base metal, HAZ, fusion line and weld metal. Color etching technique [19, 20] was used for the identification of solidification modes such as primary ferrite, primary austenitic and eutectic types. The samples, welded under different heat input conditions, were studied with the help of optical microscope at different magnifications. A large number of color photomicrograph were taken at magnification of X100, X200 and X500 in different regions along cross sections transverse to direction of welding and parallel to the bead surface to study the soundness of the weld and the nature and type of microstructure obtained. These photomicrographs are very useful in studying the mode of solidification, morphology of ferrite and the effect of complex and varying heat input flow pattern at the areas of bead overlap and other zones of overlap. Typical color photomicrographs depicting different modes of solidification, different morphology of ferrite, complete coalescence in fusion boundary are included in this thesis.

1.4.5 MICROHARDNESS DISTRIBUTION
Extensive microhardness survey of the weld samples were carried out to correlate microstructure and microhardness to achieve a high degree of confidence in predicting microstructure of the weld. Microhardness was measured across sections perpendicular to welding direction covering weld metal, fusion line, HAZ (Heat Affected Zone) and unaffected base metal resulting from welding and is presented in graphical form for easy and quick analysis in chapter V.

1.4.6 DELTA FERRITE MEASUREMENT
Austenitic stainless steel weld metal is generally designed to contain 3 to 13 % of delta ferrite in its microstructure in order to increase the resistance to solidification cracking and the corrosion resistance properties [21]. Hence, delta ferrite content of the austenitic steel weld metal and its morphology were studied using Fisher ferrite scope on the samples used for bead geometry study. Mathematical model was developed correlating pulsed GTAW process parameters with delta ferrite. Using the model, the direct and interaction effect of varying the process parameter with delta ferrite was studied and presented in chapter V.
1.4.7 CORROSION STUDIES

Weldment formed from the high temperature fusion of stainless steel can be made either with or without the addition of filler metal (latter being termed as autogenous welding), which can markedly affect the microstructure of the weld, surface composition and subsequently the corrosion behavior of the fabricated joint in service. A number of factors may cause the poor corrosion performance of stainless steel weldment, including poor design, welding practice and sequence, shielding gas composition, incomplete weld metal penetration, porosity, surface contamination, cracks, residual stresses, use of improper filler metal and final surface finish [22]. In some service environments, these may cause Crevice Corrosion, Stress Corrosion Cracking (SCC), Intergranular Corrosion (IGC), Pitting Corrosion and Galvanic (dissimilar metal) Corrosions [23]. Based on literature survey, four basic mechanisms that can lead to corrosion problems in well fabricated stainless steel weldment are carbide precipitation (sensitization) in HAZ, crevice corrosion of weldment defects, preferential attack of weld metal precipitates and pitting of alloy depleted regions in weld metal.

Corrosion can range from the most encountered general corrosion to one of the highly localized types- such as pitting, crevice, IGC and stress corrosion cracking (SCC) [24-28]. The stainless steel weld must resist several type of corrosion, like general corrosion and localized corrosion. Although uniform attack is detrimental, it is at least predictable on the basis of laboratory and field-testing and that allowance can be made for it at the design stage. Localized corrosion attacks can take place both in the base metal as well as in the weld metal because of their microstructure and compositional heterogeneities. Weld metal sometimes inherently more prone to corrosion than the unaffected base metal. Though the basic corrosion mechanism are the same, a majority of the failures in the component that occur either during fabrication, storage, and transportation or in the service, which can be directly or indirectly related to corrosion of weldment. Hence, detail studies on corrosion of weldment such as pitting and IGC were carried out.

1.4.7.1 PITTING CORROSION STUDIES

In view of wide variation in heat input, different fusion welding process may affect the delta ferrite content and morphology, which in turn may affect the corrosion behavior of austenitic stainless steel weld. In low carbon austenitic stainless steel where sensitization
is not a major problem, weld metal may be the most corrosion prone for localized pitting corrosion [29]. Hence, the pitting corrosion studies on the austenitic stainless steel weld were conducted using Potentio dynamic anodic polarization test which is accelerated electrochemical corrosion test in chloride solution as per ASTM G5 standard. The pitting corrosion resistance parameters like Corrosion Potential ($E_{corr}$), Critical Pitting Potential ($E_{pit}$), Protection Potential ($E_{prot}$) were measured from the test [30-32]. Mathematical models were developed based on response measured in the pitting corrosion test. The mathematical model thus developed was tested for accuracy by ANOVA analysis and found to confirm with the predicted results with reasonable accuracy. The main and interaction effect of pulse current GTA welding variables on the pitting corrosion resistance parameters like $E_{corr}$, $E_{pit}$ and $E_{prot}$ were also studied and the results are presented in chapter VI.

1.4.7.2 INTERGRANULAR CORROSION STUDIES

Stainless steel weld were subjected to Intergranular Corrosion (IGC) which may occur near HAZ of base metal, leading to failure of the weld. The susceptibility to IGC is due to the precipitation of chromium carbide at the grain boundaries when a weld metal is exposed to critical temperature of 450$^\circ$ to 870$^\circ$C. In this temperature range, the precipitation of these high chromium carbide at the grain boundaries removes chromium from the matrix adjacent to the precipitates leading to IGC. The chromium content in the depleted region is considerably lower than that (about 18%) of the undepleted portion of the grains. As a result, these depleted regions may be subjected to rapid preferential attack.

Several methods are available for quantifying the degree of sensitization, a number of which have been standardized in ASTM A262 (1978). Four of these, practice B through E, involve prolonged exposure of the steel to boiling acid solutions and are thus unsuitable for field use. The fifth method – practice A, electrolytic etching in oxalic acid followed by metallographic evaluation of the etch structure, is relatively simple to perform, but in its present form, has the disadvantage of not giving quantitative results. Electrochemical Potentiodynamic Reactivation (EPR) technique is an electrochemical method of testing IGC by assessing sensitization at grain boundaries that satisfies both demands of quantifiability and applicability to field-testing. Hence, EPR technique was chosen for the present investigation, since it is most popular, quantitative, nondestructive
testing and rapid method to detect the IGC [33]. Among the available EPR test, namely single loop EPR [34] and double loop EPR test [35], double loop EPR test was chosen for the IGC test. It has higher reproducibility, independent of surface finish of the weld specimen, insensitive to variation in scan rate and concentration of activators in the electrolyte. Moreover, unlike single loop EPR, double loop EPR test requires no grain size measurement. The ratio $I_r / I_a$ between the peak currents on the reverse and anodic scan is taken as the measure of degree of sensitization [35]. The welded specimens are polished to 600 grit finish with SiC paper using standard metallurgical method. Double EPR test was conducted on weld specimens and $I_r / I_a$ ratios were calculated. Mathematical model was developed correlating pulsed GTAW process parameters with $I_r / I_a$ ratio and presented in chapter VI.

1.5 SEQUENCE OF INVESTIGATION

Having decided the plan of action, it was imperative to carry out the investigation in such a sequence so as to involve the least duplication of work and time saving. The sequence of the present investigation is depicted in Fig.1.2.

To start with, trial runs were conducted to find the limits of the process parameters and to facilitate the design of experiment for the development of mathematical models. Thus a design matrix based on central composite design of five level three factor full factorial was evolved. Experiments were conducted as per the design matrix and bead geometry study was carried out to develop mathematical equations for the prediction of bead dimensions for stainless steel welding using pulse current GTAW process. From the mathematical models developed, process parameters were predicted to have full penetration. The welding was carried out using the predicted process parameters and the measured bead dimensions of the weld were found to be in good agreement with their corresponding predicted values. Model developed were also used for optimizing the weld bead area by having other important bead parameters as constraints to get a minimum weld bead area without sacrificing the quality of the bead for cost saving purpose and full penetration weld.

Detailed metallurgical investigation followed by the study of bead geometry of weld samples was made, which includes microhardness survey, delta ferrite measurement, macrostructure and microstructure studies. Final part of the investigation deals with the evaluation of pitting and intergranular corrosion resistance of the weld using Potentio...
dynamic anodic polarization test and Double loop Electrochemical Potentiokinetic Reactivation (EPR) test technique for IGC corrosion studies.

In the light of above mentioned chronology of investigation, different chapters in this report are incorporated in the following sequence: Introduction, Literature survey, experimental design, development of mathematical models and optimization of bead geometry, metallurgical studies and corrosion studies. The conclusion of all phases of investigation is summed up in the last chapter, which is followed by a list of references used for different chapters. Following the list of references is the appendix, which includes the practical data and optimization procedure not described in the main write up.
FIG. 1.2 SEQUENCE OF RESEARCH WORK