ROBOT BASED 3D WELDING FOR JET ENGINE BLADE REPAIR AND RAPID PROTOTYPING OF SMALL COMPONENTS

BY

SANTOSH KUMAR THUKARAM

A Thesis
Submitted to the Faculty of Graduate Studies
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Mechanical and Manufacturing Engineering
University of Manitoba
Winnipeg, Manitoba, Canada

ACKNOWLEDGEMENTS

Pursuing my Masters in Mechanical and Manufacturing engineering at the University of Manitoba has been one of the most rewarding experiences. Living and studying in Winnipeg has left me with valuable lessons and fond memories. I would like to thank god for his love and kindness which is unparalleled.

I will forever be indebted to Dr. S. Balakrishnan for giving me this opportunity to work under him. I have benefited immensely from Dr. Bala’s knowledge and teaching methods. I thank him for the research assistantship provided. He has always been helpful, supportive and has encouraged me to the fullest extent. I would like to thank Dr. N.L Richards for being my co-advisor and allowing me to use his robot which was a treat to work with. Dr. Richards’s friendly attitude and the ease with which he can be approached deserve special mention. I thank him for guiding me throughout the research work many times when my knowledge regarding the subject was lacking. I would always consider it a privilege to work under both Dr. Bala and Dr. Richards.

I wish to thank the University of Manitoba for providing me with this opportunity. I thank the University for awarding me the IGSES and the Manitoba Graduate Scholarship which have been of invaluable help in completing my masters. The scholarships have allowed me to focus completely on my studies and are a major reason for my success in the course work and the research as I was able to devote my entire time towards it.

I would like to thank Don Mardis and Mike Boskwick from the metallurgy lab for always being kind enough to spare time for me. I would also like to thank Ken Tarte of the Robotics and Automation lab for his support with building my fixtures and tools. I must thank technicians of the machine shop and all the others from the department of Mechanical engineering for always being willing to help. I would like to thank Mrs. Janaki Balakrishnan for welcoming me to Canada when I first arrived here and helping me get settled in Winnipeg during the first few days.

I wish to thank my parents without whom I would never have achieved anything in life. Their love, patience, support and understanding is the only reason I have come this far. I would also like to thank my sister for her support and kind words and my little nephew who thinks I'm his brother. I would like to thank my friends who have made my stay in Winnipeg so wonderful. Last but not the least I would like to thank all the special people in my life.

Thank you everyone who have made this possible…

Santosh Thukaram

ABSTRACT

Engines are one of the most critical parts of an aircraft. They are made up of a large number of blades which are subject to wear and other types of damage during the course of operation. These blades are expensive and must be repaired wherever possible. In addition engines have small components which are required in small numbers. These need to be developed rapidly and at a lower cost than conventional manufacturing methods.

The first part of this research work focuses on developing a robust automated blade repair method using robotic welding. Weld parameters such as current, voltage, wire feed rate and travel speed were optimized to produce the desired weld geometry. Optimal weld parameters were also developed for build-up of edges having different thicknesses. Samples with varying Current of 40, 45 and 50 Amps and varying travel speed of 0.13, 0.16 and 0.19 m/min were produced and their micro hardness values were compared. Blade profiles with varying weld cross sections were also welded upon.

The second part involves a methodology for producing small components using rapid prototyping (RP) techniques. This part involves use of 3D robotic welding for layered manufacturing. Heat management issues were tackled while depositing multiple layers of metal. Optimal weld parameters were developed to ensure uniform weld geometry. Offset between weld passes was fine tuned to ensure proper overlap of weld passes to obtain parts that are free from voids. Testing of the tensile samples produced using the metal RP method resulted in an average Yield stress of 346.65 Mpa, UTS of 565.4 Mpa and Elongation of 21.3 % which was found to be well above the minimum cast specifications for the given material.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

I - INTRODUCTION

1.1 MOTIVATION

Maintenance, repair and overhauling (MRO) of gas turbine engines is a multimillion dollar industry. With several new airlines emerging every year in both commercial as well as freight sectors there is a rapid increase in air transport. Cheaper air fares due to severe competition have further influenced the rise in air travel. Emerging economies of the east have taken to air transport like never before. Traditional methods of shipping have been replaced wherever possible to shorten delivery times. All this has given rise to increase in production of aircrafts. With the number of aircrafts in the market on the rise and airline operators trying to stretch the operation capabilities of the aircraft, the MRO industry has been put under immense pressure.

The maintenance, repair and overhaul industry had been hitherto catering to a limited number of clients and aircrafts. The industry mainly depended on skilled workers and machinery required for the job. Automation was minimal and never close to that found in automotive companies. With this rise in the number of aircrafts the MROs have to increase their productivity and delivery times. Airline operators are constantly looking to reduce their downtime.

One of the most critical parts in an aircraft is the jet engine. The gas turbine jet engines of aircrafts require periodic maintenance to achieve their full operational capabilities and to prolong their life. Gas turbine engines and the hundreds of components it contains are expensive. The casing, blades and small components are the ones that most often need to be repaired or replaced.

Every jet engine contains hundreds of blades. Most of these blades get worn out during normal operation and some get damaged. The worn out blades need to be repaired or replaced depending upon the amount of damage sustained. Blades are expensive and hence they are repaired wherever possible. Repair is usually manual, time consuming and requires highly skilled labor. Even with highly skilled laborers repairs are prone to defects, rejections and other quality issues. On the other hand the aerospace industry unlike automotive or other mechanical industries requires certain parts in small numbers. Conventional manufacturing methods such as casting prove extremely expensive for a small number of parts. Large lead times associated with the parts are a major setback.

This research work is divided into two parts. The first part is concerned with automating the blade repair process. It involves the use of robotic welding that will make use of optimized weld parameters, to be determined as part of this research. This part contains the development of weld parameters based on the weld geometry. The objective is to demonstrate the advantages of automated blade repair such as producing welds of required geometry, controlled heat input and superior mechanical properties.

The second part involves a methodology for producing small components using rapid prototyping techniques. This part involves the use of the robot for layered manufacturing. The objective is to be able to achieve optimal parameters to ensure that fully dense parts are produced. The aim is to show that it is possible to produce small components using robotic welding as a metal rapid prototyping technique, where the parts fabricated consist of many layers of deposited metal and each of these layers are made up of several weld passes. Analysis of the properties of the parts produced will further justify welding based rapid prototyping as a quick and cost effective alternative to conventional manufacturing methods. The next few sections will present some basic information that is useful to understand the repair and deposition process and the rationale for choosing the selected final approach.

1.2 GAS TURBINE BLADES

The blades are critical parts found in a gas turbine. The blades are mounted on disks and each disk will have several blades attached to it. There are a number of such disks in every engine bringing the blade count per engine to several hundred. The type, size and number of blades vary with the type of engine.

Gas turbine engines are made with very tight tolerances. During normal operation the blades rub against the casing liners causing wear at the edges. The blades are designed to operate for a specified number of hours after which they must be inspected for defects and repaired or replaced based on the extent of damage. Each blade can cost hundreds of dollars and every engine has hundreds of such blades and hence replacing all the blades can be a very expensive. At the same time blades are critical components and one faulty blade can lead to the failure of the engine. There exist very strict guidelines for blade repair and re-use. Hence the challenge is to make a repair of high quality which can function as good as the original blade. This has to be done within the desired time and at a cost which makes it feasible.

The common defects that occur in gas turbine blades are damage to the blade tips, blade seal fins, nicks, dents, distortion, airfoil surface defects and blade cracks. Depending on the extent of damage some of these defects are repairable and some blades have to be rejected. The focus of this thesis will be on repair of defective and damaged blade tips.

The most common type of defect that occurs in gas turbine blades is a damaged or worn out tip. Over extended periods of operation the blade tip is worn out. Wear on blades is more pronounced around the edges. Edges can also break or chip away. Repair of these edges requires re-construction of the profile. Conventional repair methods involve manual welding of the damaged portion and then machining which can involve grinding / polishing to attain the required profile dimensions.

Automated repair involves the use of sophisticated machines such as robots and CNC machines to repair the blade. Figure 1.1 shows a conceptual model which highlights the general steps that could be involved. These steps are indicative and hence some or all of these steps may be required in the repair process.

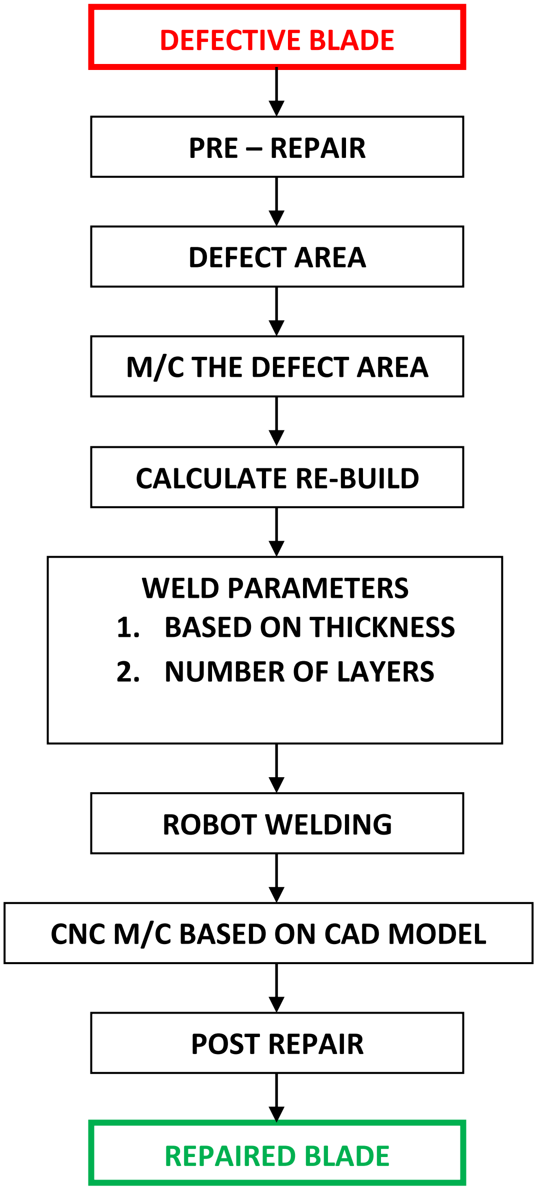


Figure 1.1 – STEPS INVOLVED IN AUTOMATED REPAIR OF BLADES

- **PRE – REPAIR INSPECTION**

This is the first step in which the blade is inspected for the defect. The defect area is identified and decision on whether or not the repair is possible is made at this stage.

- **DEFECT AREA**

Once the defect has been identified the amount of material from the blade tip that needs to be removed and repaired is established.

- **MACHINING THE DEFECT AREA**

The blade is machined to a pre – determined point from the tip and the blade surface is prepared for welding

- **CALCULATE REBUILD**

The cut blade is measured and measurements compared with a CAD model. The amount of material build-up required to reconstruct the blade is determined.

- **WELD PARAMETERS**

The weld parameters required are calculated from the database. The database contains information on the weld parameters required to obtain the necessary weld thickness for the given material. The number of layers of weld metal required to replace the cut portion of the blade is also calculated.

- **ROBOT WELDING**

The robot program is generated with these weld parameters for the given blade profile. The robot commences welding of the blade which is handled and monitored by an operator.

- **CNC MACHINING**

The blade after welding will be in a near net shape. The blade is then machined in a CNC machine based on the CAD model to obtain the exact dimensions.

- **POST REPAIR INSPECTION**

Once the repair is completed the final step is to compare the blade with the original CAD model. The blade can also be subjected to non – destructive testing methods such as ultrasonic testing.

1.3 ADVANTAGES OF AUTOMATED REPAIR OVER MANUAL REPAIR

Automated repair has several striking advantages when compared to manual repair. The important advantages which make automated repair the preferred method for blade repair are.

- **WELD PARAMETERS**

  The weld parameters are of high importance as they directly affect the heat input which in turn affects the physical as well as mechanical properties of the weld. The weld parameters vary based on the cross section to be welded and hence the robotic welding produces a more precise weld. In comparison a manual welder does not have control over the heat input while welding a varying cross section. This is even more important in the case of a blade as the blade is a relatively small part and hence even a small change in parameters will affect the outcome of the repair.

- **SUPERIOR QUALITY**

  Automated repair produces a blade of superior quality. Individually designed weld parameters for each blade and particular defect produces unparalleled quality. Robotic welding also ensures that the weld is defect free. The subsequent CNC machining will ensure that the repaired blade is made to exact dimensions. In the case of manual repair such quality can only be produced by highly skilled labor and seldom at such speeds.

- **INCREASED PRODUCTIVITY**

Automated repair significantly reduces the repair time. Robotic welding and machining is much faster when compared to manual welding. More blades can be repaired in the same time thereby increasing the productivity.

- **CONSISTENCY**

A major advantage of automating any process is the consistency that comes with it. Hundreds of blades can be repaired with the same level of accuracy in repair work. The accuracy and precision of work does not decrease with increase in the number of blades.

- **REDUCED COST**

The superior quality and increased consistency ensures that there are few rejections. Reduction in scrap increases the productivity and reduces cost. The high cost of machinery involved is offset by the number of parts being produced. These investments are long term and break even is quick when compared to the high costs associated with skilled labor.

- **SAFETY**

Welding has always been considered as a health hazard. The bright arc combined with the fumes involved is very harmful. Even with adequate protection long term welding can cause irreparable damage. Such concerns are removed with the use of the robot. The operator is only used to setup the part and make or edit the program. Therefore automated repair improves the overall safety associated with blade repair.

1.4 SMALL COMPONENT MANUFACTURE

Conventional methods to manufacture or fabricate small components are casting and machining. Both casting and machining are well established methods for manufacturing components in large scales. The dies and moulds are expensive but reusable and hence the process is also cost effective. These two methods have proven to be the default method in the case of mass production.

In some industries like the aerospace industry there is a need for components in small numbers. Conventional methods like casting require a large lead time to prepare the moulds and these become very expensive when used to produce only a small number of parts. Machining involves fabricating the component from a solid block of metal. Aerospace alloys are expensive and this type of machining increases the cost of the component. Conventional methods also make use of several jigs and fixtures which are part specific. These further add to the cost of the manufactured component and are rendered useless when changes are made to the components. Therefore the time involved in obtaining the components and the high cost need to be overcome.

1.5 RAPID PROTOTYPING AS AN ALTERNATIVE METHOD

Rapid prototyping is also known as stereo lithography, solid freeform fabrication (SFF) [1], desktop manufacturing, layered manufacturing, automated fabrication, and tool-less manufacturing. [2]. Some of the definitions for rapid prototyping (RP) are:

A collection of technologies that are driven by CAD data to produce physical models and parts through an additive process [3].

The speedy fabrication of sample parts for demonstration, evaluation, or testing. It typically utilizes advanced layer manufacturing technologies that can quickly generate complex three-dimensional objects directly from computer-based models devised by Computer Aided Design (CAD) [4].

Rapid prototyping is the automatic construction of physical objects using additive manufacturing technology. The first techniques for rapid prototyping became available in the late 1980s and were used to produce models and prototype parts [5].

Rapid prototyping as the name suggests was used to make quick prototypes of parts. Prototypes are required to test the aesthetics, ergonomics, design and functioning. To rapidly develop products the new product development lifecycle has to be short. Therefore companies and industries are looking for new time compression techniques (TCT) such as RP. RP parts can be produced in a few days, parts having complex shapes and internal cavities and features can also be made. Since peripheral fabrication such as tools and dies are not required RP is cost effective for manufacturing parts with small lot sizes. RP is also a good candidate for automation. There are several methods of RP being widely used around the world such as stereo lithography and 3D printing.

The prototypes produced have the exact shape of the product but are seldom made from the right material. It can be used to manufacture parts made of wax, plastic, nylon and polycarbonate. Certain good RP techniques can produce parts that have exact dimensions and tolerances. Occasionally plastic products can be prototyped in the exact material. There are also examples of functional and moving parts produced by RP techniques. The major disadvantage is that these prototypes cannot be used for physical testing while making prototypes of metal parts. Conventional RP cannot be used as a method to directly manufacture parts.

1.6 METAL RP

The advantages that RP offers, high speed, no moulds or dies, minimal jigs and fixtures and the ability to immediately transition from a 3D CAD model to the manufactured part makes it an enviable process and one that would do wonders if incorporated to manufacture metallic parts.

Over the years numerous research groups and companies are trying to develop a reliable process to reap the benefits of metal RP. Metal RP has posed several challenges in achieving the same level of quality of conventional manufacturing processes. Some of the challenges are in maintaining the right density, uniformity of the material throughout the part, avoiding pores and voids in the material, inclusions and defects and surface finish. Relative success is said to be achieved when a part can be manufactured to near net shape. Component of exact dimensions can be obtained by subjecting it to minimal machining and finishing operations.

1.7 WELDING AS A RAPID PROTOTYPING METHOD

Welding has always been considered as a robust joining method and the quality of joints produced are comparable with the parent material in terms of mechanical strength. Welding consists of depositing metal by melting weld wire or filler metal. Therefore welding can be considered as an additive process. Welding is usually done in passes and these passes can be used in a clever manner to form layers of metal needed to build parts through RP similar to stereo lithography. Welding has evolved from modest manual welding techniques to completely automated robotic welding. The use of sophisticated robots and control systems together with their integration with computers and highly capable software packages can help make welding a stand alone RP technique.

Some of the advantages of welding over other metal RP techniques are as follows:

- **METAL DEPOSITED IN MOLTEN STATE**

In welding the metal is melted and the molten metal is deposited thereby having similarities with casting process. Complete melting of the metal is ensured as compared to sintering where powdered metal is sintered to form solid raising issues of variation in density.

- **EQUIPMENT READILY AVAILABLE**

As highlighted earlier state of the art welding robots and robotic work-cells like the one used for this research are readily available and these can be used directly for metal RP with little or no modification.

- **SIMPLE METHODOLOGY**

Standard welding practice can be used to make overlapping passes and multiple layers to form a near net shaped part which can then be subjected to finishing operations. There is nothing new in the methodology as only standard, tried and tested welding methods are used.

- **COST EFFECTIVE**

Welding does not require additional machinery and exotic materials. The simplicity of the process and little or no further machining makes it a cost effective method to produce parts quickly and as needed.

1.8 WELDING

The American Welding Society (AWS) definition for a weld is,

A localized coalescence (the fusion or growing together of the grain structure of the materials being welded) of metals or non metals produced either by heating the materials to the required welding temperatures, with or without the application of pressure, or by the application of pressure alone and with or without the use of filler materials [6].

Welding has a long history and has been developed from a primitive joining process to the state of the art precision welding robots of today. Welding is directly or indirectly used in almost every man made object we come across in our daily lives. From dental braces, household appliances, computer components, farm equipment, construction, bridges, towers automobiles, earth moving equipment, ships, aircrafts and space shuttles and even in the machines that make these machines. Welding is therefore a valuable process widely used in all types of manufacturing. It has been perfected to reap maximum benefit from it [7].

1.9 WELDING AND ALLIED PROCESSES

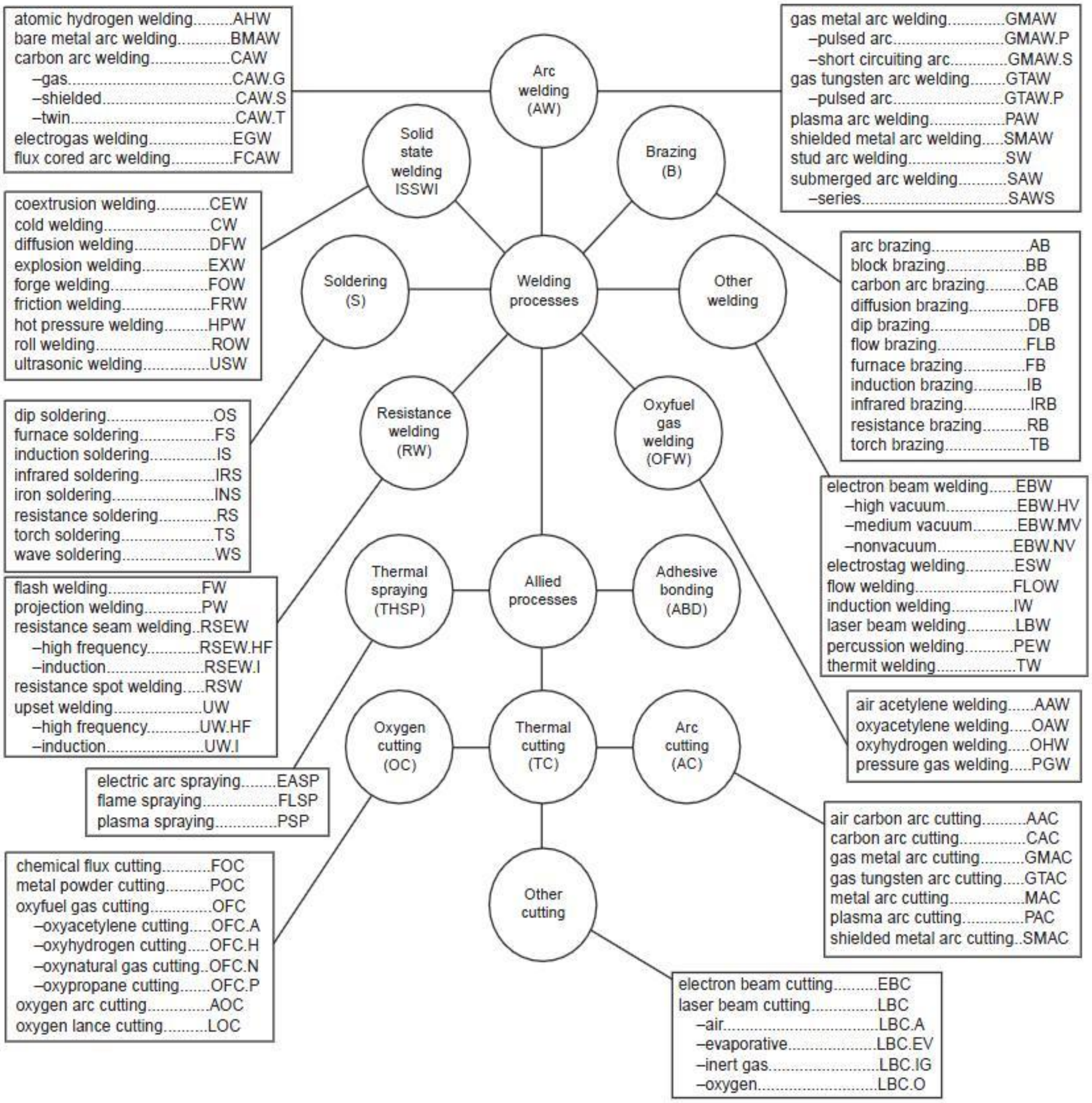


Figure 1.2 – MASTER CHART OF WELDING AND ALLIED PROCESSES [6]

It can be seen from Figure 1.2 there are innumerable welding methods, some with small differences and some completely different from each other. Selection of the appropriate method depends on several criteria such as quality of weld required, work location, materials to be joined, size of the parts to be joined, cost of materials and many other specific requirements.

Arc welding is a common and widely used welding method in which an electric arc is struck between an electrode and the work piece such that the heat generated is sufficient to melt the filler wire or material or metals themselves. Definitions for arc welding are:

Arc welding uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes [8]

A group of welding processes wherein coalescence or complete fusion is produced by heating with an electric arc [9].

The two most widely used arc welding methods are Gas Metal Arc Welding (GMAW) also known as Metal Inert Gas Welding (MIG) and Gas Tungsten Arc Welding (GTAW) also known as Tungsten Inert Gas (TIG) welding.

a. GAS METAL ARC WELDING (GMAW)

Gas metal arc welding (GMAW) is a welding process which joins metals by heating the metals to their melting point with an electric arc. The arc is between a continuous, consumable electrode wire and the metal being welded. The arc is shielded from contaminants in the atmosphere by a shielding gas.

The schematic in Figure 1.3 shows a typical GMAW setup which consists of the power source, the weld wire fed from a spool of wire to the nozzle or welding gun. The wire strikes the arc with the work piece. The shielding gas used is an active gas such as carbon dioxide and oxygen. The welding gun delivers the electrode wire and the shielding gas to the area being welded.

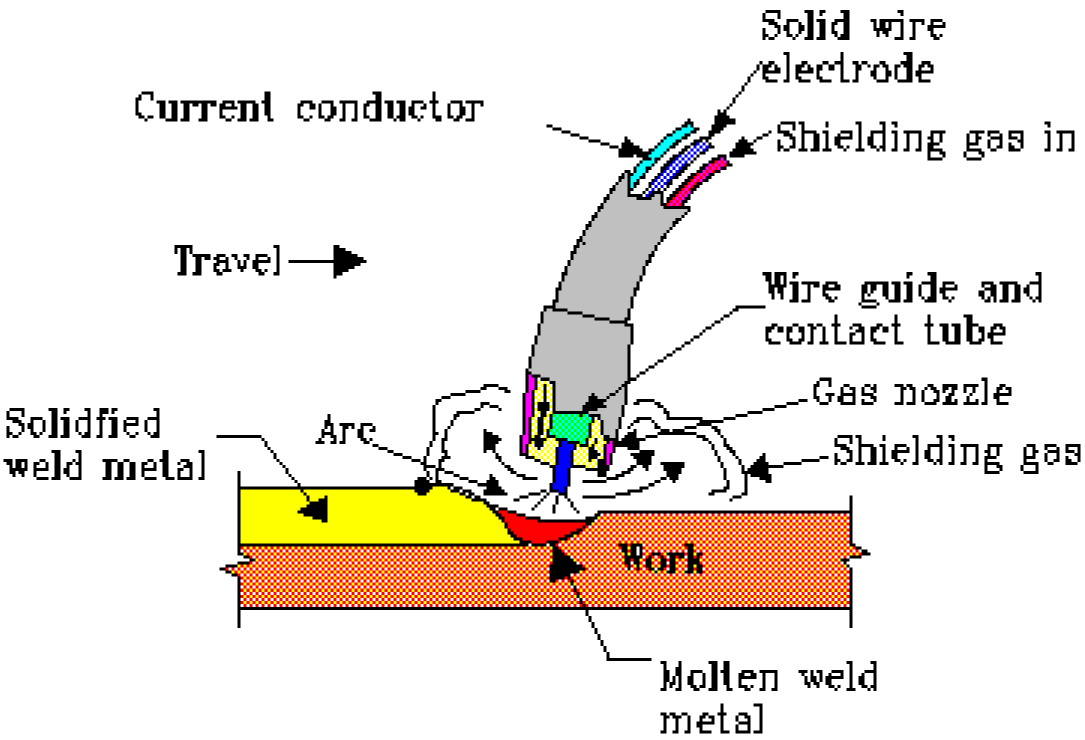


Figure 1.3 – GMAW SCHEMATIC [28]

- **GMAW APPLICATIONS**
  - It can be used for welding of carbon, silicon and low alloy steels, stainless steels, aluminum, magnesium, copper, copper, nickel and its alloys and titanium among others.
  - It is used for welding tool steels and dies
  - It is used in automotive, pressure vessel and ship building

b. GAS TUNGSTEN ARC WELDING (GTAW)

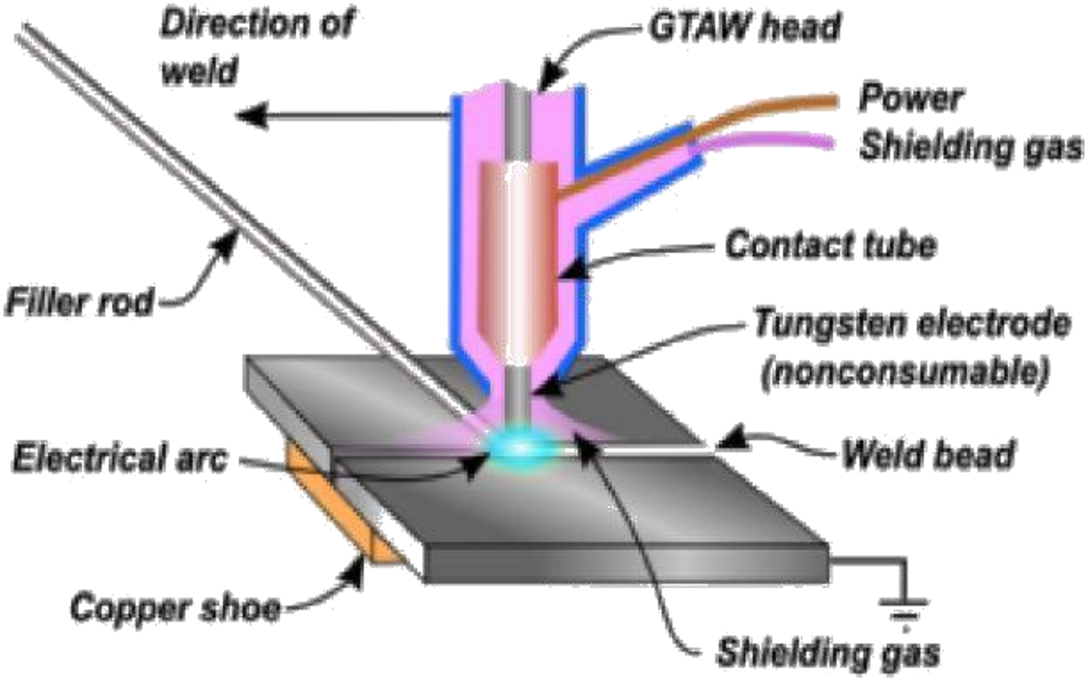


Figure 1.4 – GTAW SCHEMATIC [29]

Gas tungsten arc welding (GTAW) is a welding process which joins metals by heating the metals to their melting point with an electric arc. The arc is between a non-consumable tungsten electrode and the part to be welded. The arc is shielded from contaminants in the atmosphere by an inert shielding gas. The inert gas used is deficient in active chemical properties and protects the weld from oxidation.

The schematic in FIG 1.4 shows a typical GTAW setup which consists of a power source. The electrode is the non-consumable tungsten rod. The arc is struck between the tungsten electrode and the work piece. The filler material or filler rod is external and is introduced into the arc manually or through a wire feeder.

- **GTAW APPLICATIONS**
  - Welding aluminum, magnesium, copper, nickel and its alloys, carbon, alloy or stainless steels, Inconel, high temperature and hard surfacing alloys like zirconium and titanium.
  - Used for precision welding in atomic energy, aircraft, chemical and instrument industries.
  - Welding of sheet metal and thin sections

1.10 ADVANTAGES & DISADVANTAGES OF GTAW

GTAW was chosen as the preferred method because of the advantages it has over GMAW. GTAW also suits the current research work of repairing gas turbine blades and is also highly suitable for robotic welding which takes care of its inherent flaws.

ADVANTAGES

- **HIGH QUALITY CLEAN WELDS**

GTAW produces welds of superior quality. The welds are visually as well as mechanically sound and hence it is the preferred method for important welding tasks.

- **WIDE RANGE OF METALS & ALLOYS**

It has the capability to weld a wide range of metals and alloys.

- **SAFETY**

It is a better welding method because there is no spatter, slag, sparks or smoke.

- **EASE OF WELDING**

GTAW allows for welding in all positions.

DISADVANTAGES

The two main disadvantages of GTAW are

- **LOWER DEPOSITION RATES**
- **HIGH LEVEL OF OPERATOR SKILL**

The above disadvantages are easily overcome by the use of the robot. Lower deposition rates are ideal for welding thin blades and the deposition can be easily increased by the use of the wire feeder. The robot easily fits into the definition of a highly skilled operator and hence this is no longer a concern with the use of the robot. Therefore GTAW is the ideal choice with respect to the quality of weld required, material being welded, size of the part and equipment being used.

This chapter has provided a discussion on gas turbine blades and blade repair in general. This was followed by advantages of automated repair over manual repair. The need for small component manufacture and use of rapid prototyping techniques were also discussed. Metal RP and the use of welding as a RP technique were explored. In welding GMAW and GTAW were compared and GTAW was chosen due to the advantages it provides. Considering all of this it was decided to use robotic welding for automated repair of gas turbine blades and manufacture of small components using rapid prototyping techniques.

The second Chapter contains a review of related literature. A complete literature survey was done and key areas of the problem highlighted. The second chapter also provides information on how other authors and researchers have tried to solve similar problems. Their methods and the advantages and limitations have also been reviewed.

The third Chapter deals with experimental techniques. Here the various methods and equipment used to conduct the experiments are discussed. The testing and results obtained are contained in Chapter four. All the experiments conducted are discussed in detail and placed in order for easy understanding. The results obtained from mechanical testing were tabulated and analyzed. The final Chapter of the thesis is the discussion, conclusion resulting from this work and future directions. Here an inference is drawn from the results obtained. The findings of the research work are highlighted. The application of this research work and potential future work is also contained in the last Chapter.

II - LITERATURE REVIEW

2.1 INTRODUCTION

In the first Chapter gas turbine blades and choices for repair work as well as the need to manufacture small components quickly by using rapid prototyping techniques were discussed. Conventional rapid prototyping and metal RP were also discussed. The reason for choosing GTAW and its advantages were also highlighted. With this knowledge one can now proceed to review the relevant literature which will give one an insight into the research work conducted by various students, researchers and manufacturers at different universities and labs around the world.

This research work is divided into two sections, one on jet engine blade repair and the other on small component manufacture. With this in mind the literature review can also be divided into similar sections. This Chapter will focus on gas turbine blade repair and reconstruction and Metal RP for the manufacture of small components. The final section will be a discussion on the literature reviewed. The focus of this research work and how it differs from the literature reviewed as well as its importance will also be discussed.

While reviewing the literature it was found that some approaches are on similar lines and hence while writing this review an effort has been made to amalgamate them into one while still discussing about all aspects put forward by the different authors. In some parts especially the metal RP section the different techniques and methodologies used by the different authors have been dealt with one at a time and a brief summary on each method has been provided.

2.2 GAS TURBINE BLADE REPAIR AND RECONSTRUCTION

All parts and components such as tools, dies and parts of gas turbines undergo operational wear and tear. Critical components can be affected by change in dimensions due to deformation [10]. High temperature and pressure as well as foreign object impact leads to distortion, wear, dents and cracks [14]. Conventional repair procedures are mostly manual and therefore experience based [11]. It involves removing the worn out region of the blade tip, replacing the worn-out portion with metal deposition by welding and finally machining, grinding / polishing to complete the repair [12]. They are inefficient and prone to errors. Poor quality of repair and inability to recreate the geometry directly affects the performance of the engines [11].

Therefore such components cannot be repaired by comparing them to their original CAD models. Hence it becomes necessary to create a CAD model of the damaged part from scan data before any additive or subtractive processes such as welding and machining respectively are carried out on it as part of the repair. One common approach is to use polygonal modeling using 3D scanning data to achieve defect free models. The polygonal model is simpler and quicker than conventional surface modeling [10]. Similar methods for capturing the geometry of the worn area and subsequently utilizing the information for comparison and repair have also been used in other works. Use of reverse engineering techniques to capture the geometric shape of the worn area by digital point cloud and nominal geometry was part of a proposed system which involves 3D scanning, broken boundary extraction and triangular mesh generation [11]. A robust profile reconstruction (RPR) algorithm which as the name suggests can be used to reconstruct the profile by using the neutral line concept and the interpretation vector method by finding the relationship between the original profile of the blade and the used blade under each section layers in a two dimensional plan [12]. Adaptive machining strategy is a novel method for automating repair and overhaul of aero engine components. Adaptive machining tends to reduce variations between the repaired parts. The numerical control (NC) paths adapt to the particular part that is being machined by using in–process measurement tools and mathematical best fit strategies. A data management system is a significant part of any automated overhaul system. It stores all the data, for example machining paths, as data sets for each type of blade. Depending upon the type of blade the particular data set is used [13].

In the 3D non-contact measurement based blade repair integration system [15], the repair system consists of the non-contact 3D digitizing system which acquires the blades geometrical data and creates the CAD model. The pre-repair inspection, build-up, adaptive grinding / polishing and the final quality inspection modules interact at each stage with the information integration environment.

3D digitizing is a very important part of the entire process as the quality of the final repaired product depends on the accuracy with which it is done. The digitizing system should be capable of acquiring accurate measurements from the worn out blade. The 3D data acquired can be easily transferred in any of the standard forms for post processing. Conventional pre-repair inspection is manual and depends on the judgments of the quality inspector. In this system they have proposed an automatic pre-inspection procedure based on the data obtained from the 3D digitizer. These data are compared with that of a CAD model and the repair area is identified and the system takes the decision based on a set of rules [15].

A polygon model of the blade is created and this information is used for the build-up. The challenge is to create an accurate polygon model with least number of polygons. The build-up technology also involves adaptive welding / cladding and machining. The weld path is based on the blade top profile. The weld can be one pass along the centre line of the curved blade profile or multiple passes along the outer edge of the blades and the choice entirely depends on the size and shape of the blade. Further machining processes are carried out using a five-axis machining centre [15].

The repaired blade is again digitized to get its CAD geometry. This is aligned with the original CAD model to compare dimensions. The system has the capability to check blade height, chordal length and air foil thickness at specific points [15].

The implementation of a similar strategy was done on HP compressor blades [14]. The scanning was performed by the GOM ATOS II – 400 3D non-contact optical measurement systems. Three dimensional co-ordinates for up to 1.3 million data points are calculated by the digitizing system. These data points were used to form polygon models and exported in common formats such as IGES and STL. The machining is done using a developed 3 Axis machining system. The machining system has to precisely remove the necessary amount of excess material from the weld to achieve the required dimensions. The machining is done with appropriate path and tool selection. For accurate machining, it is done in several steps namely rough cut, semi finish and finish cuts. The machined blade is then subjected to the post – repair inspection where the quality of the repair is evaluated [14].

2.3 THE WELDING TECHNIQUE

The research work discussed up to this point concentrates on the blade repair process as a whole with emphasis on automating the process and executing it with minimal or no human interference. The actual weld build-up and build-up strategy has not been discussed. There is little information available on selection of weld parameters and edge build-up of blades. One research group from the Singapore Institute of Manufacturing Technology has done work on precision welding for edge build-up [16].

Although a lot of development has been made in the field of welding, welding on thin edges continues to be a difficult and challenging task. Research on edge build-up of thin walls for applications such as jet engine knife edge seals has highlighted the challenges of welding on thin edges. Welding on thin edges is different from normal welding used for various joining operations. Knife edge seals require precision welding with controlled heat input [16]. They have used TIG or GTA Welding as opposed to GMAW because of the quality and precision that can be obtained by GTAW. They have also experimented with the dabber method wherein the weld wire is fed in an intermittent manner. This method helps for deposition of finer droplets of weld beads. The current is also pulsed such that weld wire is fed at the point when the current is at its highest thus minimizing heat input to the work piece. The material used for their experiments is mild steel and stainless steel. The welding system used was a computer controlled Hobart HPT-300 multi-arc welding system. The system is controlled using a programmable teach pendant [16].

From the above literature it was found that it is easier to build as the thickness of the edge increases.

- Welding parameters were obtained for plates of varying thicknesses from 1 mm to 3 mm.
- The wire diameter must be optimal because a thin wire causes an unstable weld pool and the bead size produced is irregular. If the weld wire is too thick then the current is not sufficient to melt the wire.
- The relative position between the welding torch and the wire feed nozzle is also important because it ensures that the wire enters the arc at the appropriate position.
- One of the most important parameters is the weld current. If the current is too high then it can melt the edge being welded. High current can also melt the weld wire excessively and

cause an uneven weld. The excessive melting also reduces the height of the weld deposit and can affect subsequent layers of the weld.

- Voltage is another important weld parameter. Automatic Voltage Control (AVC) was used in these experiments to maintain a constant voltage. The voltage influences the heat input and optimal heat input is preferred as stated before [16].

In this paper a series of experiments with different weld parameters were necessary to obtain the optimal weld parameters. The weld samples were micro sectioned and metallurgical analysis was done on them to determine the quality of the welds. While welding very thin edges having a thickness of less than 1 mm it is necessary to melt the edges initially before welding. This is to obtain a much more even and flat surface than a very sharp edge. When the arc is struck without first melting the edge it burns the edge and causes the material to collapse. The process of melting the edge before welding is called MELTDOWN. Meltdown is done with a very small current just sufficient to melt the edge. The arc length is critical because the vertical movement of the torch can cause the weld to be uneven. The optimal parameters they obtained were then used to weld the jet engine knife edge seals. For welding on a circular edge the work piece is rotated. The advantage of rotating the work piece is that an even tolerance can be maintained as the welding torch is stationary [16].

2.4 WELDING PATH PROGRAMMING FOR AEROFOILS

One of the most important aspects of automated welding is to generate the welding path. The path which usually consists of a series of individual points can be used to generate the required arc depending on the shape of the blade. This section will discuss an early research work in which the concept of segments and use of different weld parameters for different segments depending on the required weld geometry was developed.

To teach individual weld points the torch has to be moved to the appropriate location and saved as a weld point. The accuracy of the weld depends on the number of points chosen on the curvature. The position of the weld points can also be used to determine the start and end of weld segments each having a different set of weld parameters. The curve fitting function ensures a smooth transition between segments while welding [17].

Multiple passes may be required to achieve the required build-up on the tip. The research has shown that automated welding is able to produce repairs of higher quality and consistency when compared to manual repair. The researchers also feel that automated welding can improve productivity as the same setup can cater to a wide variety of gas turbine blades [17].

2.5 RAPID PROTOTYPING OF METAL USING GTAW

The need for rapid prototyping of metal parts, use of welding as a RP technique and the choice of GTAW has been previously discussed in the first Chapter. This section will consider the work that has already been done in this area. Different approaches and methods of metal RP using GTAW are reviewed and methods have been summarized to get a glimpse of the various methods.

Rapid prototyping generally consists of a 3D CAD model of the part to be produced. The part is divided into sections or layers usually having the same thickness. These are stored in the STL file format and read by the RP system to deposit metal as per the 2D shape given in each STL file. The number of layers deposited adds to form the final 3D product. Metal RP aims to produce parts of near net shape which require little machining or finishing operations to obtain the final desired dimensions.

2.6 STL DATA PROCESSING

STL data processing for rapid prototyping using GTA welding has also been discussed in the literature [18]. Their experimental setup consists of a NC milling machine, GTAW apparatus and an embedded fibre-optical subsystem [18].

In their research the concentration was on converting the CAD file into slices / layers in such a way that an accurate and error free final part can be obtained. Often when files are converted and imported in STL format there may be some errors in the conversion such as gaps, aberrance and missing facets. It is important to detect and fix these errors. The slicing thickness is decided and the slicing direction also needs to be optimized. Depending upon the STL model we can have different types of slicing algorithms. There can be real--time slicing and non-real-time slicing. The welding deposition and milling operations are based on NC codes [18].

2.7 WELDING PARAMETERS

Regardless of the equipment used or the method adopted for metal RP, welding parameters and determination of the weld seam dimensions are important to ensure accurate deposition, optimal overlap between passes and flat even layers. In an automated system these parameters would ideally be stored in a database and the system will retrieve the data as and when required. However two models based on BP neural networks which can be used to predict the optimal welding parameters for a desired type of weld seam have been developed [19]. One model can predict the weld seam dimensions if the weld parameters are input and the second model can predict the weld parameters given the weld seam dimensions [19].

The way in which these models are used is as follows. First the required weld seam dimensions are input into the second model which predicts the weld parameters. The weld parameters are then varied slightly if necessary to suit the requirements and equipment capabilities and then these modified parameters are fed into the first model which predicts the weld seam dimensions. The parameters considered are the current, voltage and wire feed rate which influence the height and width of the weld. If the current is too low then there will be insufficient heat to melt the wire and therefore a continuous weld deposit cannot be obtained. On the contrary if the weld current is too high then the excess heat will melt the wire and a portion of the substrate and the weld height will be low and of poor quality [19].

Their experimental setup consisted of a GTA welder. Water cooling was employed below the substrate to ensure proper cooling. The experiment consisted of welding a single track of a specified length and measuring it at different intervals while varying the parameters. The next step was to train the neural networks. Once trained the models can be used to predict the appropriate weld parameters for the required weld seam dimensions.

2.8 RAPID PROTOTYPING METHODS AND EXPERIMENTAL SETUPS

- **RAPID PROTOTYPING OF ALUMINUM ALLOYS**

A novel layer deposition technique based on variable polarity GTAW using which a hollow cylindrical part with 120 layers was produced and its properties were studied [20].

The RP equipment involves a Variable Polarity Gas Tungsten Arc Welding (VP-GTAW). The welding torch was fixed to the vertical axis and the substrate is fixed to the rotary table. Numerous single pass layers were made to select the right kind of weld and the corresponding weld parameters to produce this type of weld. It was found that the welding speed is an important factor and has a direct influence on the height and width of the weld. The welding speed will also determine the heat input to a particular area and the depth of penetration. Similarly, the wire feed rate also has a major role to play on the type of weld deposit. If the wire feed rate is high then high welding arc energy is required to melt the wire. Again by varying the wire feed rate, the quantity of weld deposit in terms of height and width and the penetration depth can be controlled [20].

While building layered structures it was seen that the first layer bonded well with the substrate and no metallurgical defects were observed. The subsequent layers melted a portion of the previous layer and formed a good bond on solidification. A hollow cylindrical part with 120 layers was produced. It was observed that the heat input needs to be higher for the first few layers at the bottom because of higher heat dissipation and as the number of layers increased the heat input had to be decreased, to obtain similar weld deposit as the bottom layers. Therefore a good heat input control is needed depending upon weld thickness and width required as well as the material of the filler wire. On the surface of the wall fine striations were observed which were formed at the interface of the different layers [20].

The part was sectioned and its microstructure was observed in different regions at different heights. The microstructure of the different layers, the bonding zone and the heat affected zone were studied. The upper regions exhibit a fine dendrite structure while the lower regions exhibit a coarse dendrite structure. The hardness is lowest at the bonding zone and the lower regions of the wall have a smaller hardness value when compared to the top layers of the wall. This is because of overexposure of the bottom walls to heat [20].

Further research using VP GTAW on 5356 aluminum alloys has been done. Post processing testing which involves the testing of micro hardness and surface roughness has given more knowledge about the properties of the weld produced [21]. The micro hardness varies with variation in the weld parameters and also depends on the location of the measurements. The hardness of the equiaxed grains of the deposited layer is higher than that of the bonding zone and the heat affected zone. The material of the top layers is much harder when compared to the rest of the part. The hardness gradually increases from the base upwards. The surface roughness was measured and it was found that the roughness in the vertical direction on the side-walls is approximately ten percent more than the horizontal direction. It was also found that as the height of the layer increases, the surface roughness of the wall also increases due to the arc-length variation [21].

- **RAPID PROTOTYPING OF NICKEL ALLOYS**

Direct deposition of a nickel based alloy called Waspaloy has been studied at the University of Nottingham [22]. Waspaloy displays high strength at high temperatures. They used a KR15/2 6 axis robot to which a Hitachi power source was attached. The base plate is also made of Waspaloy. The weld parameters were optimized until a sound weld bead having uniform bead size and no external defect was obtained. Thin wall blocks were built using this process. The blocks were cross-sectioned and mounted. Micro hardness measurements were done on these samples. The blocks were made of both GTAW and laser welding. The microstructure and hardness was compared for both methods [22].

- **RAPID PROTOTYPING OF STEELS**

A steel rapid prototyping system using GTA welding fitted onto a CNC milling machine was developed [23]. The welding data were sampled through a computer which was connected to the system. Using this setup the position and motion of the welding torch can be controlled using the CNC machine. The wire feed and welding torch parameters were controlled from the computer. To ensure a steady stream of droplets the wire feed and the weld parameters had to be optimised. Constant wire feeding was chosen and this was achieved by using a stepper motor. The droplet transfer method is called ‘metal bridge transfer’ because the metal is transferred from the weld wire to the weld pool via a liquid metal bridge [23].

Based on this research the authors found that the thickness of each layer as well as the width and thickness of each weld is important. These play a major role in how the final part is produced. The weld geometry is directly influenced by the weld parameters. Another important factor to be considered while depositing multiple layers each having multiple passes is to establish an optimum offset between passes. The offset amount affects the amount of overlap which influences the evenness of the layer and ensures that there are no gaps or voids between passes. In normal GTA welding the heat induced varies over the length of the weld, especially at the point where the arc is struck and at the end. Therefore there is a variation in thickness along the length of the weld. The weld is thick at the beginning and maintains an even thickness over the normal length of the weld. It tends to gradually slope towards the end. This effect is amplified as many number of layers are deposited leading to uneven thickness of layers and deviation from the desired shape. Therefore automatic arc length and voltage feedback control was used.

Another example of robotic welding for metal rapid prototyping uses a welding robot for deposition of metal and the advantage mentioned is that different metals can be used on the same part as it only involves change of the weld wire [24]. 3D CAD model of the part is built using AutoCAD. Layer specific information also needs to be input. Once all the information is input into the part then automatic slicing is done to divide the part into different layers. The robot program is created to follow the path described by the sliced layers. The robot based RP system was used to make simple parts such as a small vase and exhaust manifolds [24].

Robot based shape metal deposition and its control was studied and a control method developed for shape metal deposition. This paper discusses aspects related to transfer of heat during welding, such as the effect of parameters on the amount of heat input such as the increase in heat with reduction in travel speed [24]. Again the increase in current causes increased heat input and a thicker welding pool.

In the shape metal deposition process as in any RP process, increase in number of layers increases the overall appearance and adherence to dimensions. Therefore it is important to select the optimal layer thickness. Based on this they have defined the four important parameters as, arc current, wire feed rate, travel speed and the thickness of each deposited layer. Their automated control system for metal deposition is based on the amount of material deposited in each layer. The information on the amount of metal deposited is obtained from arc emitted light, arc emitted sound and arc voltage.

- **3D MICRO WELDING**

In order to make the literature review complete, concepts in metal RP known as 3D micro welding are also considered. In 3D micro welding the tip of a thin welding wire is melted to form a small metal bead. The metal beads are overlapped and arranged into layers. Layers on layers of beads are deposited in the required fashion to obtain the 3D part. It was possible to develop a fully dense object using this technique. Free form fabrication of superalloy objects by 3D micro welding is being researched at the Osaka University in Japan [25].

The 3D micro welding apparatus consists of a forming station, an arc control unit, system control computers and a video monitoring device. The table in the forming station is capable of movement in the X and Y axes and the welding torch moves in the Z axis. As with other metal RP techniques the 3D CAD model is sliced into several layers. The difference in 3D micro welding is that each layer is very thin and needs to be less than the height of a single bead. Beads are arranged to form layers and other layers deposited on previous ones. Tensile samples were made and their tensile strength, elongation, ductility and other mechanical properties were measured. These were compared to the standard metal and found to be in the same range [25].

2.9 SUMMARY

From the literature it can be seen that different methods and various equipment have been used both for blade repair and component build-up. Each has its own advantages and disadvantages with respect to cost involved, quality, speed and productivity. The salient features of this research project in comparison to the literature reviewed are highlighted below.

- **WELDING PROCESS**

In most of the papers reviewed the researchers have concentrated mainly on the development of automated repair systems in the case of blade repair and rapid prototyping systems for component build-up respectively. In blade repair, more emphasis has been given to digitizing, re-modeling of blade profile and development of software for reconstruction of the blade profile. In rapid prototyping the papers mainly review the slicing and layer deposition strategies and the equipment developed for this purpose.

In both cases not much emphasis is placed on the actual welding process and how the weld parameters and welding process will affect the outcome. Regardless of the system used the welding process is of paramount importance to ensure high quality repairs and rapid prototyped parts. It is for this reason, in the current research work importance has been given to how the various parameters were established. The selection of optimal parameters and which critical variables affect them will be discussed. The welding process was followed by mechanical testing to evaluate the quality of the weld produced.

- **ROBOT**

The use of different equipment for both blade repair and component build-up has been discussed. Modified CNC machines with welding torches attached to them are the most common. For component build-up most equipment are 3 axes, 2 axes X and Y for the movement of the table and the Z axis which is the vertical movement of the torch. This type of system is functional and suitable for simple parts and repairs not requiring high tolerances. On the other hand some of the equipment has been setup and built for this particular purpose with custom software thereby increasing the cost, difficulty in availability of parts and expensive overall setup.

The solution to this problem is to use welding robots. The advantages of using robots for welding have been discussed. Robotic welding has been perfected over the years and is being widely used. The ability to produce high quality repeatable welds is important to the aerospace industry where these blades will be repaired. Hence the robot is the ideal choice for such a project.

- **BLADE REPAIR & COMPONENT BUILD-UP**

In this research both blade repair and component build-up are considered. Both require welding and rapid prototyping techniques for reconstruction of the blade and part build-up respectively. Though they seem similar in certain aspects they are entirely different when it comes to actual welding.

Blade repair involves precision deposition of metal. Welding has to be done with least heat input depending upon the thickness of the blades being welded. Varying cross – section blades are more complicated as different weld parameters have to be used to achieve different thicknesses. On the other hand component build-up poses different challenges. Here the amount of metal deposited is much larger. The weld parameters are different to achieve higher deposition rates. Heat management is critical and hence optimal weld parameters need to be used. Another important aspect is the overlap between weld passes which should be optimal to ensure that there are no gaps and voids.

The literature review has also given several important inputs. Mechanical testing in terms of micro hardness and tensile testing to evaluate the repair and parts produced is important. The critical variables which affect metal deposition will also be assimilated from various papers. The literature also provides a basic over view of the process before actual experimentation in this project. With this knowledge we can move on to the next chapter wherein the experimental techniques developed will be presented.

III - EXPERIMENTAL TECHNIQUES

In this chapter an overview of the experimental techniques and the equipment used will be provided. As a first step the wire material, the base material and their dimensions are provided. The welding technique using the robot and a brief outline of robot programming and how the robot operates is discussed. The welding methodology which forms the backbone of this research is discussed in detail with illustrations. The sample preparation method is described in brief. Micro hardness testing and tensile testing are discussed in detail and the results of these experiments are in the next chapter. The final part of the chapter contains the sequence of experiments.

3.1 MATERIAL

- **BASE MATERIAL**

To establish the optimal weld parameters for blade repair the base material used was stainless steel. Strips of steel were cut from a large sheet of the material to be used as test coupons. These were 100 mm X 30 mm and increased later to 150 mm X 50 mm in dimension. Stainless steel was chosen as the material as it was readily available and economically viable when compared to expensive nickel alloys. The same material of 3 mm thickness was used for experiments on edge build-up as well. To establish weld parameters for different thicknesses these strips were rolled into test pieces having different thicknesses of 0.5 mm, 1 mm, 1.5 mm, 2 mm and 2.5 mm.

Sample blade cross-sections were cut from a 10 mm thick rectangular slab of cast Inconel 718 by electric discharge machining (EDM). The metal deposition for the tensile samples as well as for the final component build-up was done on rectangular blocks of Inconel 718, 25 mm thick. Welds were also made on real blades which were obtained from industry.

- **WIRE MATERIAL**

The weld wire used was a spool of Inconel HX also known as Alloy X or Hastalloy X. It is a Nickel base superalloy which has outstanding high temperature strength and oxidation resistance. It also has excellent resistance to carburization and nitriding. It exhibits good ductility and can be machined when annealed. Most of the commonly used fusion and resistance welding techniques shown earlier in Figure 1.2 can be employed to weld the alloy. It is widely used in gas turbine components. Table 3.1 gives the chemical composition of Hastalloy X.

ELEMENT	% BY WEIGHT
Carbon	0.05 - 0.15
Chromium	20.5 - 23.0
Cobalt	0.5 - 2.5
Iron	17.0 - 20.0
Manganese	1.0 max
Molybdenum	8.0 - 10.0
Nickel	Balance*
Silicon	1.0 max
Tungsten	0.2 - 1.0
Phosphorus	0.04 max
Sulphur	0.03 max

TABLE 3.1 - Limiting chemical composition for Hastalloy X, % by weight [1]

*Reference to the balance of the alloy’s composition does not guarantee this is exclusively of the element mentioned but that it predominates and others are present only in minimal quantities.

3.2 ROBOT

The Robot is the most important part of this research work. This section will highlight the importance of employing a robot with a brief introduction. The advantages of using robots for this particular application, the details of the robot used and the setup are discussed together with robot programming.

- **ROBOT**

Robots are increasingly being used in most industries and manufacturing companies because of the innumerable advantages they offer. The main advantages are direct increase in cycle time and productivity. Robots offer remarkable quality in the operations they perform. This is mainly due to their very high accuracy and repeatability. Well maintained robots offer good reliability. Robots can be readily used in hazardous environments and to perform tasks that are injurious to human workers thereby improving safety.

Industrial robots can be used to perform a wide variety of tasks. They can be used for various applications and in different industries. Based on their application area industrial robots can be mainly divided into three types namely robots for welding applications, material handling applications and other applications.

1. WELDING APPLICATIONS
    - Arc welding
    - Resistance welding
    - Electron beam welding
    - Robot laser welding
    - MIG welding
    - TIG welding

- Plasma cutting
- Welding automation

2. MATERIAL HANDLING APPLICATIONS
   - Dispensing
   - Packaging
   - Injection moulding
   - Palletizing
   - Machine loading
   - Part transfer
   - Machine tending
   - Pick and Place
   - Material handling
   - Press tending
   - Order picking

3. OTHER APPLICATIONS
   - Bonding / sealing
   - Milling
   - Clean room
   - Painting automation
   - Deburring
   - Polishing

- Drilling
- Robotic assembly
- Flame spray
- Robotic coating
- Foundry
- Thermal spray
- Grinding
- Waterjet
- Material removal

3.3 WELDING ROBOTS

Welding robots can be broadly classified as either RECTILINEAR robots or ARTICULATED robots.

- RECTILINEAR ROBOTS

Figure 3.1 – GANTRY ROBOT [26]

These robots are capable of linear movement along the X, Y and Z axes. In addition they have a wrist joint which is capable of adding up to 3 degrees of freedom to the robot namely pitch, roll and yaw. These robots have a rectangular work envelope. The most common robot of this type is the gantry robot shown in figure 3.1.

- ARTICULATED ROBOTS

The articulated robots are similar to the human arm. They usually have a base, shoulder, elbow and wrist. The base, shoulder and elbow are rotating joints each offering a unique degree of freedom to the robot. The wrist joint usually has three DOF namely pitch, roll and yaw. These robots usually have a quasi-spherical work envelope. Figure 3.2 shows an articulated welding robot.

Figure 3.2 – ARTICULATED ROBOT MANUFACTURED BY KUKA [27]

3.4 ADVANTAGES OF USING WELDING ROBOTS

Welding robots have several advantages when compared to manual welding. Some of the key advantages are:

- ACCURACY & PRECISION

Welding robots offer exceptional accuracy while welding and produce precision welds which can only be matched by highly skilled welders.

- REPEATABILITY & REPRODUCIBILITY

Welding robots produce consistent welds. They can produce the same weld quality over and over again.

- SPEED

Welding robots can weld at increased speeds which cannot be matched by manual welding. The increased speed increases the productivity as more parts can be welded in the same amount of time.

- SAFETY

The welding operation is hazardous as it produces a very bright arc and welding fumes. The arc is dangerous to the human eye and can affect vision even with protection. Welding fumes can cause respiratory problems and some fumes can be carcinogenic. Use of robots ensures that valuable workers do not come in contact with the arc or the fumes and involve mainly in programming the robot and setting up each operation.

- QUALITY

Welding robots produce very high quality welds which are not susceptible to operational errors often caused by manual welding. Once the robot is programmed it can produce the same high quality weld for any number of parts being produced.

- REDUCED COST

Welding robots produce high quality welds and hence there is little or no scrap involved. The increased speed results in more number of parts being produced in a given time and over continued usage the robot is a cheaper option when compared to highly skilled labour which is expensive. These advantages indirectly reduce the costs and improve profits.

3.5 EQUIPMENT DETAILS

The primary equipment used for welding on all samples is the PERFORM ARC 42 (PA 42) robotic welding system integrated with a 6 DOF PANASONIC VR-004 robot. The PA 42 is a widely used industry standard robotic welding system. The robot is fitted with a MIG as well as a TIG welder and all necessary peripherals. The control panel and welders are conveniently mounted below the robots table. The wire feeder is conveniently located so that new spools of wire can be easily loaded onto the system. Therefore the PA 42 is a self contained robot welding system shown in Figure 3.3.

The PA 42's table is divided into two halves A and B which can be used as two different work stations on either side of the robot. A mechanical vice capable of movement in both the X and Y axes was fitted onto the table to hold the samples while welding. In addition a cylinder of Argon gas is connected to the system to act as the shielding gas while welding. The system has wide sliding doors on either side which are guarded by light curtains which act as a safety preventing the operator from entering the robots work envelope during automatic operation.

Figure 3.3 – PANASONIC PERFORM ARC – 42 ROBOTIC WELDING SYSTEM [28]

The Panasonic VR – 004 robot is a versatile robot which can be used for multiple applications including welding, air plasma cutting, material handling and machine tending. It can be integrated with different controllers for different applications. The robot has 6 degrees of freedom and a payload of 4 kg. It has a horizontal reach of 947 mm and a repeatability of 0.1mm. It can be floor, ceiling or wall mounted. Figure 3.4 shows the VR 004 robot used while Figure 3.5 shows the robot's work envelope. The robot has a patented offset wrist design which enables the robot to have a very large work envelope almost covering the entire area of the PA 42's table.

The robot as well as its welding operation is controlled by a teach pendant. Programming of the robot as well as the weld parameters is done using the teach pendant.

Figure 3.4 – PANASONIC PERFORMARC VR – 004 [28]

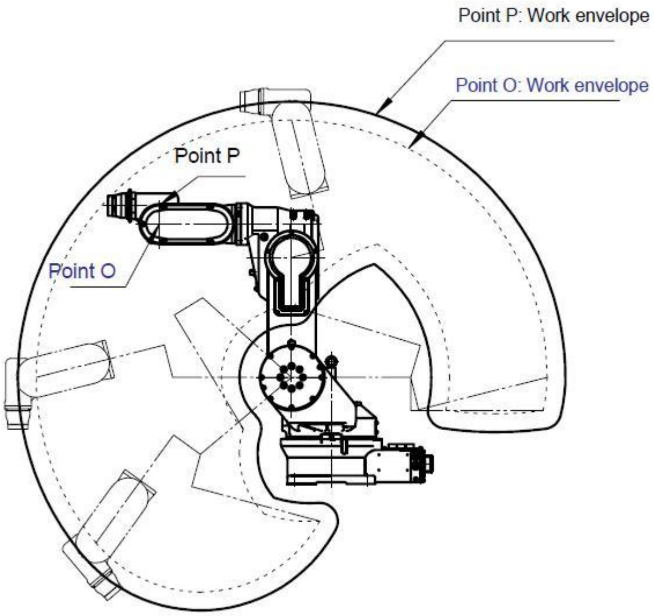


Figure 3.5 – PANASONIC VR – 004 – WORK ENVELOPE [28]

3.6 ROBOT PROGRAMMING

The robot is controlled with the help of the teach pendant shown in Figure 3.6. The teach pendant has a large screen and is controlled using the jog dial, buttons and levers found on the back. It operates on proprietary PANASONIC software which is windows based. Programs can be stored and transferred with the use of flash memory cards. G2 PC TOOLS is a software for use on the computer which can be procured from PANASONIC. Using this software programs can be written offline and then directly transferred to the robot using the teach pendant.

Figure 3.6 – TEACH PENDANT

`The teach pendant allows operation of the robot in two modes namely AUTO and TEACH. The robot is programmed using the teach mode. Test programs can be run with and without actual welding in the teach mode. The robot can be run at full speed in the AUTO mode and this has to be done with the doors closed and the operator has limited interaction with the robot in the AUTO mode.

The commands for the program can be selected from the various menus. The program consists of an initial set of commands for definition of variables being used. These are followed by commands for movement from point to point. Some of these points are AIR CUT points and some may be WELD points. In AIR CUT the robot moves from one point to another AIR CUT point or WELD point without welding, this is usually done while approaching the sample to be welded and while retreating from the sample post welding. Weld points will have additional commands to start the arc and specify weld parameters.

The movement of the robot and therefore the type of weld can be of three types:

- POINT TO POINT

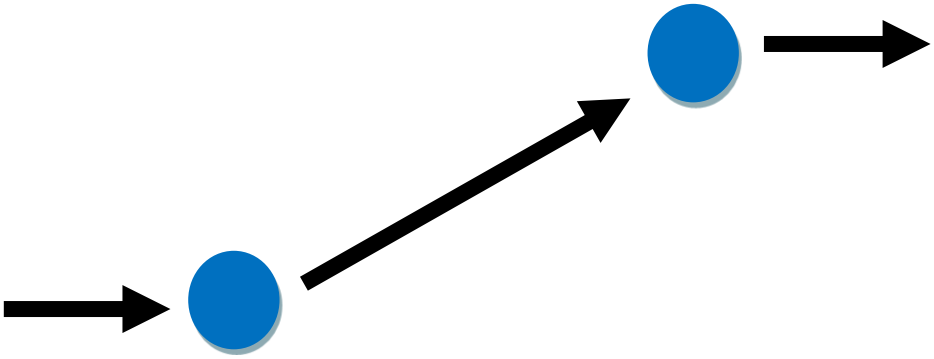


Figure 3.7 – POINT TO POINT

In this type the robot is programmed to move from one point to another point whose co-ordinates are specified or whose position is taught. The robot will move its end effector – a welding electrode – between the points using the shortest possible route. Point to point programming is used to move towards the weld section or used for SPOT WELDING.

- LINEAR INTERPOLATION

In this method the robot moves from one point to another in a straight line or linear path as shown in Figure 3.8.

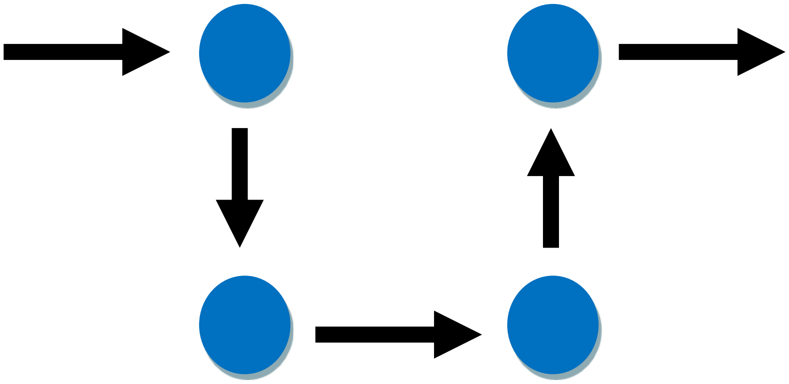


Figure 3.8 – LINEAR INTERPOLATION

- CIRCULAR INTERPOLATION

In this method the robot moves in an arc between the specified points. The usual circular interpolation command starts with an arc between 3 points. The robot can form a smooth arc between a numbers of points resulting in the desired shape of weld as shown in Figure 3.9.

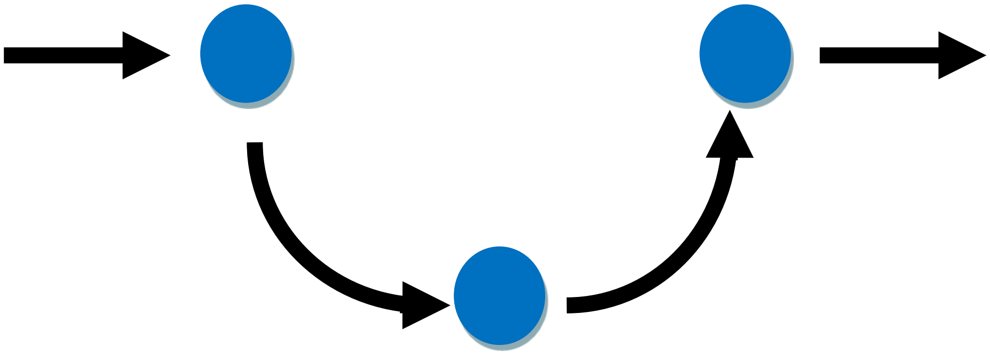
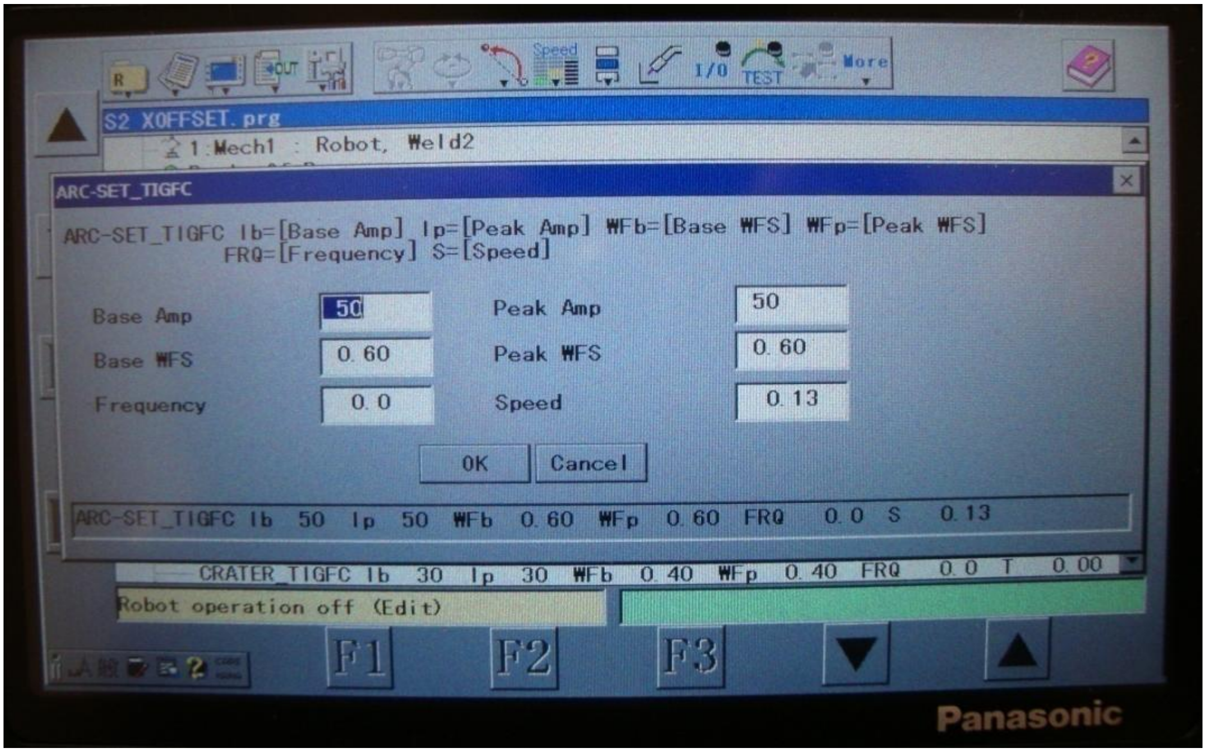


Figure 3.9 – CIRCULAR INTERPOLATION

`The most important part of the program is assigning the weld parameters. The weld parameters determine the type, quality and properties of weld produced. Figure 3.10 shows the dialog box where the weld parameters are assigned. First the arc start and delay time are input then the base and peak current, base and peak wire feed rate, travel speed and frequency – for pulsing- if any is also input. The opening and closing of the gas valve for the shielding gas and the time delay before and after the arc is set. At the end there is a crater point which has its own set of parameters for current, wire feed rate and time.



```
S2 XOFFSET.prg
1:Mech1 : Robot, Weld2
```

ARC-SET_TIGFC

```
ARC-SET_TIGFC Ib=[Base Amp] Ip=[Peak Amp] WFb=[Base WFS] WFp=[Peak WFS]
              FRQ=[Frequency] S=[Speed]
```

Base Amp	50	Peak Amp	50
Base WFS	0.60	Peak WFS	0.60
Frequency	0.0	Speed	0.13

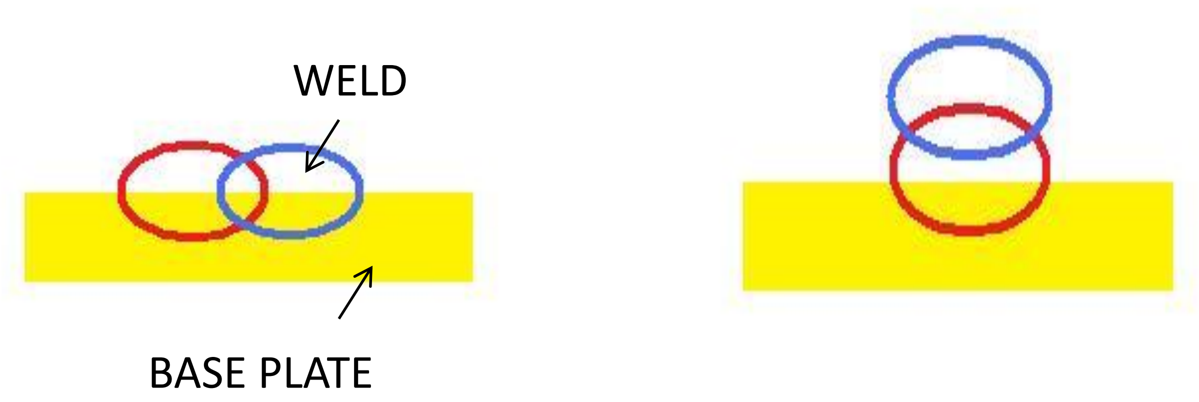
```
ARC-SET_TIGFC Ib   50  Ip   50  WFb   0.60  WFp   0.60  FRQ    0.0  S    0.13
CRATER_TIGFC Ib   30  Ip   30  WFb   0.40  WFp   0.40  FRQ    0.0  T    0.00
Robot operation off  (Edit)
```

Figure 3.10 – WELD PARAMETERS DIALOG BOX

To ‘teach’ the robot a program it has to be physically run through the entire set of operations point by point. At each point a command is added and that is how the entire program is built. Once the program is complete it can be TRACED to check for faults and to make modifications if any.

3.7 WELDING

Welding was performed by the robot. The weld path – a straight line for establishing parameters and for edge build-up welds – was programmed into the robot where the robot welds between two specified points termed linear interpolation. For welding on the blade cross-sections the programs were made with multiple points and the robot follows a circular path between the points employing circular interpolation. Weld parameters such as current, speed and wire feed are entered into the robot as part of the program. The samples were held in a vice and metal deposited on its surface by welding. Single welds or single passes were made for establishing the optimal parameters.



(a) (b)

Figure 3.11 (a) – 2 OVERLAPPING BEADS – HORIZONTAL (b) 2 OVERLAPPING BEADS - VERTICAL

For welding blades, making tensile samples and component build-up multiple passes are required both in the horizontal ‘X’ and vertical ‘Z’ directions. While making such welds it is important to ensure that there is sufficient penetration between the welds to avoid voids. It is also important to ensure that the overlap between welds is optimal to avoid non-uniformity and surface irregularities which will affect subsequent layers. Figure 3.11 (a) and (b) show the placement of welds in the X and Z direction with the penetration and overlap respectively. Figure 3.12 shows multiple layers of weld as employed to make the tensile samples.

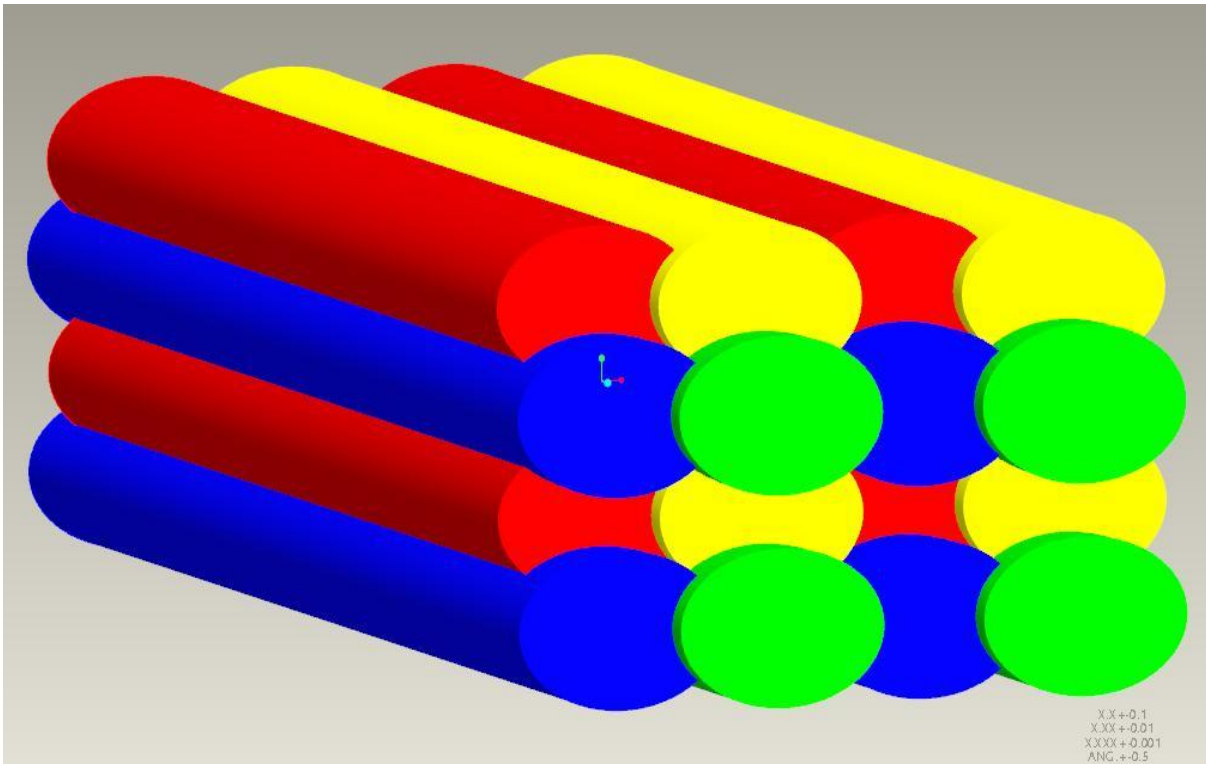


Figure 3.12 – OVERLAPPING WELDS IN THE X AND Z DIRECTIONS

3.8 SAMPLE PREPARATION

The base surface was sanded using 280 grit paper and cleaned to ensure there were no dust particles or grease. The test coupons of 25 mm thickness were mounted on the vice and welded using the robot. These were then cut using the Electric Discharge Machine (EDM). The cuts were made perpendicular to the direction of the weld to obtain a cross-section of the weld for observation. They were then cleaned to remove burrs and coolant.

The weld cross-sections were then mounted in Bakelite. The mounts were then polished using a combination of abrasive papers and diamond particles to achieve a 1 micron surface finish. Some initial mounts were polished to 1200 microns and then etched using kaling's reagent for observation under the optical microscope. Due to differential etching of the base and welds it was easier to observe the geometry.

3.9 COOLING FIXTURE

In order to reduce and eliminate the effects of warping, a cooling fixture was built. The concept was simply to pass cold water through a cooling block to take away the heat from the work piece. A 3D model of the conceptualized cooling block is shown in Figure 3.13.

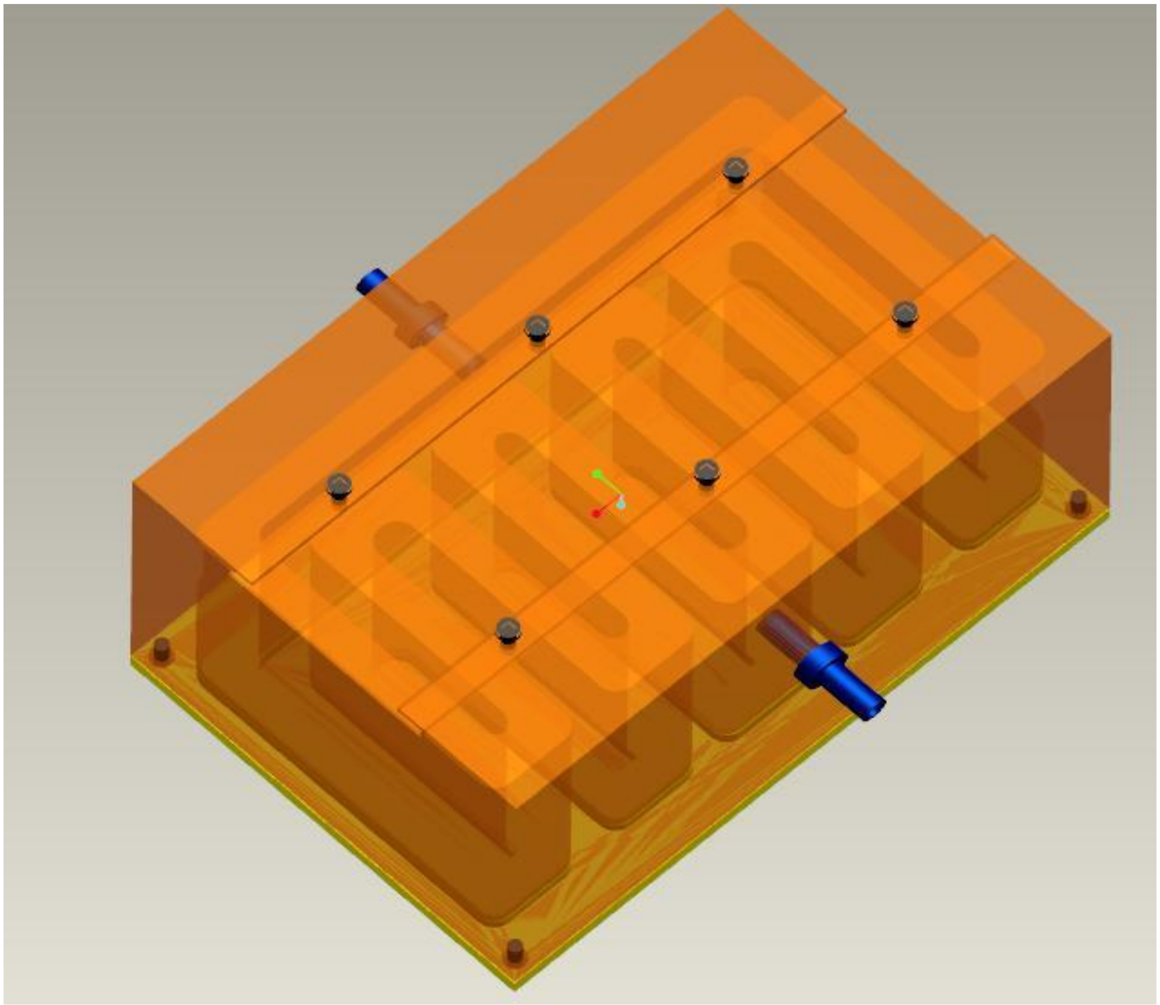


Figure 3.13 – COOLING FIXTURE 3D MODEL

The cooling fixture consists of the cooling block, a tank for the water and a pump to maintain constant flow of water, a power supply to run the pump and piping to carry the water to and from the cooling block.

The cooling block is the main unit of the cooling fixture. It consists of a solid aluminum block which is machined to allow water to channel through it and sealed tight to prevent any leakage of water. The block is shown in Figure 3.14. The cooling block has an inlet and an outlet for the water. A brass slab is fixed on top of the cooling block to prevent any direct damage to it. The work piece is held in position by two brass strips which can be tightened with screws as shown in Figure 3.15.

(a) (b)

Figure 3.14 – COOLING BLOCK – BASE & TOP

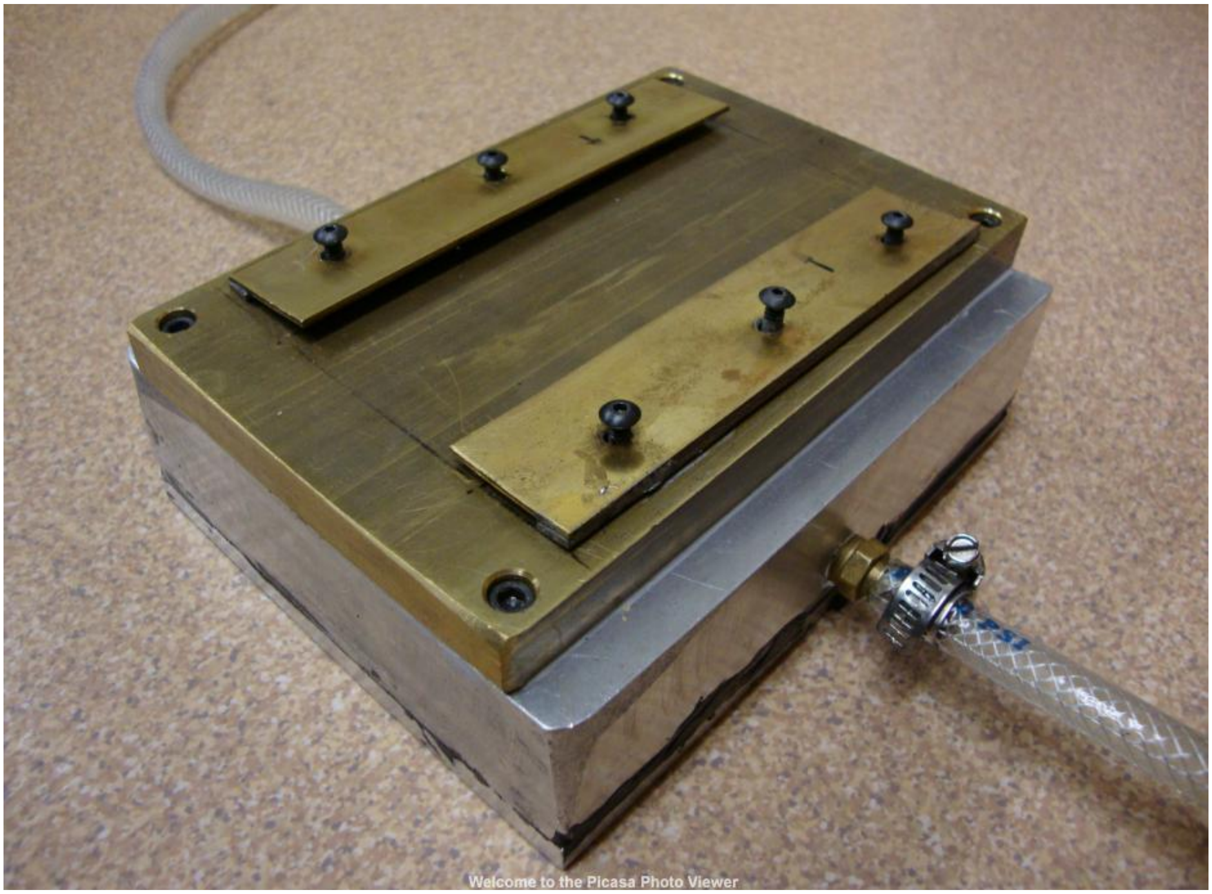


Figure 3.15 – ASSEMBLED COOLING BLOCK

A small submersible pump was used to pump the water through the pipes and into the cooling block. Figure 3.16 shows the complete cooling fixture with the power supply, water tank, and cooling block.

The cooling fixture was tested and found to be effective when the heat input was lower. The work piece was rapidly cooled to room temperature because of the heat taken away by the cold water. However at higher currents the sample continued to warp although by a considerably smaller amount.

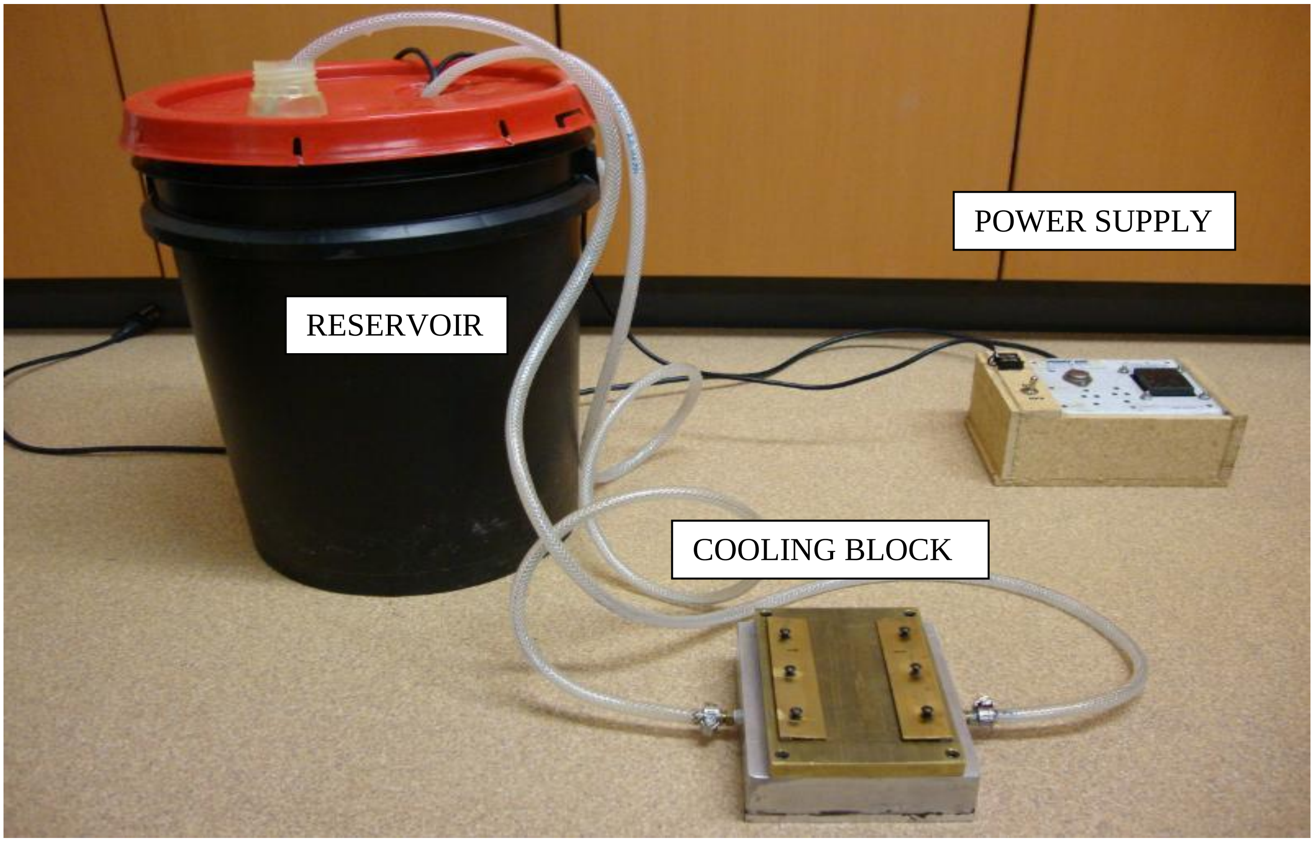


Figure 3.16 – COOLING FIXTURE

3.10 HEAT TREATMENT

After the samples were welded and sectioned they were subjected to heat treatment at 1175 degrees Celsius for 30 minutes before mounting. This was done to relieve stresses that may have accumulated when the sample was held on the vice during welding.

3.11 HARDNESS TESTING

Micro hardness testing was done on the Buehler Omnimet MHT micro hardness tester. The sample was placed horizontally in the automated turret and indentations were made as shown in figure 3.17. The direction of measurement is from top to bottom, starting from the tip of the weld and taking readings towards the base.

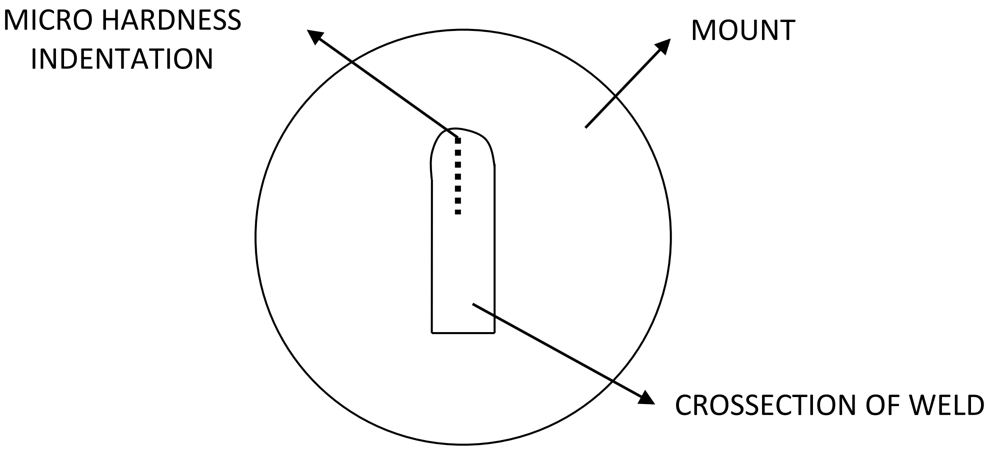


Figure 3.17 – BAKELITE MOUNT AND MICRO HARDNESS INDENTATIONS

First the table is moved to the point where the indent has to be made. This can be done by using the 10x lens and selecting the start point for measurements on the computer screen. Measurement intervals and total number of measurements or total distance covered can also be entered. The indentations were made starting at a distance of 0.25 mm from the tip of the weld and every 0.25 mm thereafter. The 0.25 mm interval is maintained to minimize any residual strain effects between indentations. The indentation is made and then the turret shifts to the 50x lens. The image appears on the computer screen where the markers can be oriented to obtain the hardness value. The hardness value of multiple points and samples can be stored on the computer and the software generates a complete report which contains the hardness readings as a table and a corresponding graph which shows the trend. The sample can then be observed under the microscope to analyze where the hardness measurements were made in reference to the position on the sample such as the weld, transition region between the weld and the base and the base.

Figure 3.18 shows one such microscopic image which shows the indentations along the weld with points on the weld material as well as on the base material.

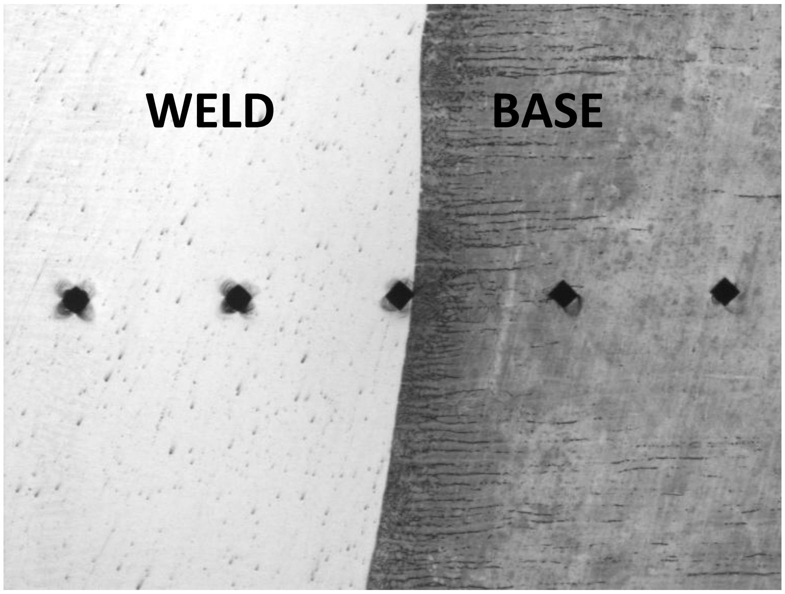


Figure 3.18 – IMAGE OF WELD CROSSECTION

3.12 TENSILE TESTING

Tensile testing was done to find properties such as the yield stress, ultimate tensile strength (UTS) and strain. For conducting tensile testing the challenge was to build a tensile test sample purely out of weld material. Multiple weld passes were made to form each layer and several such layers were built to achieve the required thickness. The weld parameters optimized for component build-up were used for making the tensile samples as a tensile sample can also be considered as a built up part. Weld parameters and the amount of overlap were the most critical factors. The X offset which determines the amount of overlap and the Z offset which needs to be done to start a new layer determine the evenness or flatness of each layer and ensure that there are no gaps, pores or voids in the weld.

Once the part had been built-up it was subsequently cut on the electric discharge machine (EDM). The tensile sample thus obtained is then polished. The gauge length of 20 mm is polished down to 600 grit.

Figure 3.19 – INSTRON TENSILE TESTING EQUIPMENT

Figure 3.19 shows the INSTRON equipment used for tensile testing. Before actual testing the cross sectional area of each sample is measured and noted down. The gauge length is marked on the sample and measured. This is to find out the length before subjecting the sample to testing.

The critical settings in the equipment are the cross head speed which determines the speed at which the sample is loaded, the full scale load value and the chart speed. The chart speed determines the speed at which the graph is drawn. The relation between the cross head speed and the chart speed is critical in determining the load being applied while reading the graph. Once the sample breaks the graph is used to calculate the following parameters.

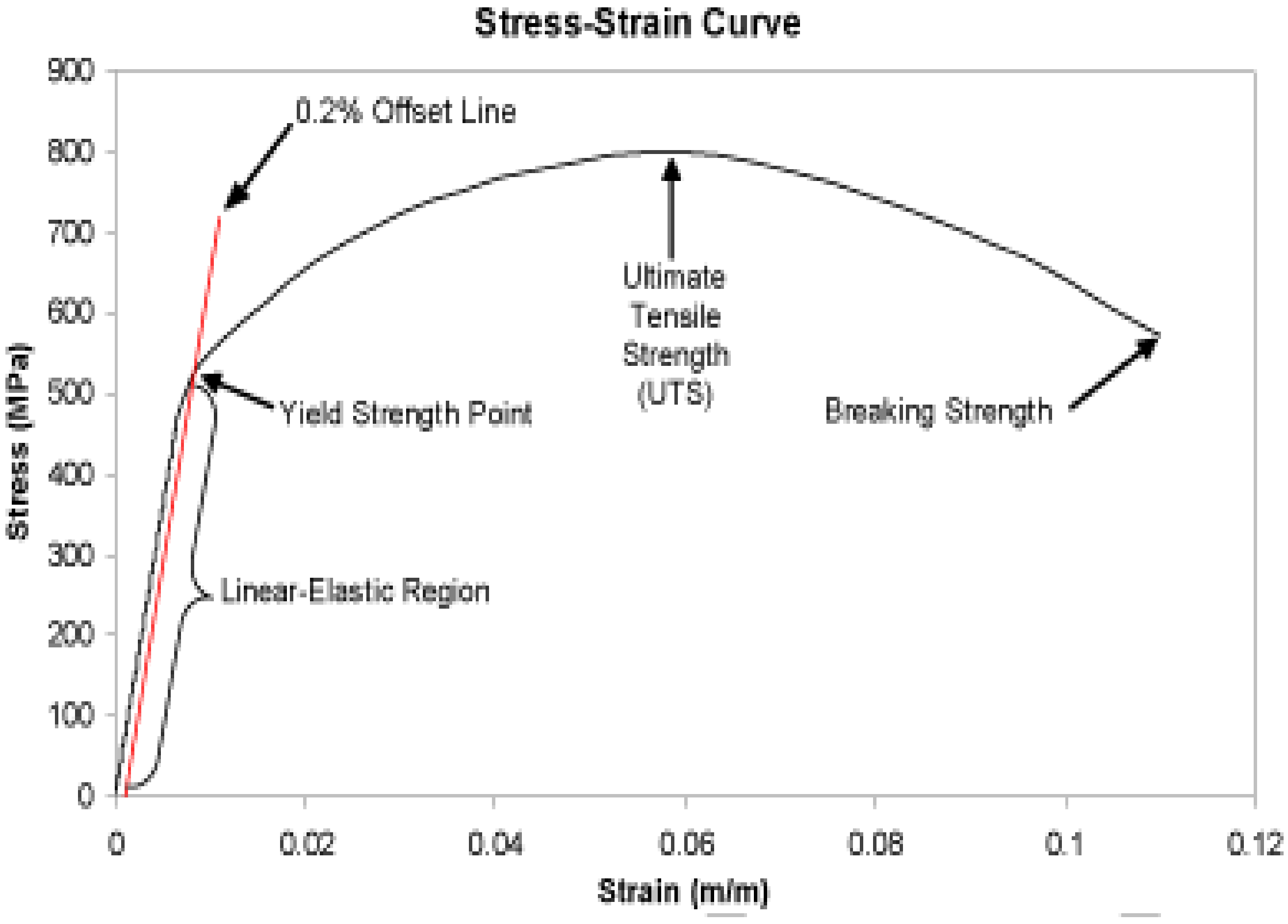


Figure 3.20 – STRESS – STRAIN CURVE

The graph obtained from the tensile test is of the nature shown in Figure 3.20. The 0.2% offset line is drawn and the point of intersection of this line with the curve gives the yield strength. Similarly the highest point in the graph gives the UTS. The strain is calculated as percentage using the difference between the initial and final gauge length and comparing it to the original gauge length. In other words it is the change in length over the original length.

These measurements allow us to compare the produced part with the standard specifications. By this method the quality of the part can be determined with respect to its mechanical properties.

3.13 SEQUENCE OF EXPERIMENTS

The experiments can also be divided into the two groups namely blade repair and component build-up.

- **BLADE REPAIR**

The main aim of the experiments is to be able to identify optimal weld parameters which can be later used to repair or reconstruct the blade profile. Initially it is essential to first establish the weld parameters for a single pass. Tests were conducted over a range of weld parameters to identify the ones that produce uniform, consistent welds with desirable geometry. Similar tests were conducted to determine the weld parameters to obtain welds of different thicknesses. The welds of acceptable visual quality and geometry were chosen and micro hardness tests were conducted. The different hardness values were compared and analysed to determine the effect of the weld parameter on the weld as well as the deposited base material.

Observation of the weld geometry and comparison of the hardness values for the various welds using different weld parameters gives rise to the optimal parameters. The next step is to demonstrate their effectiveness by creating welds with multiple layers such as a thin wall created by several overlapping welds. Further the weld parameters are used to weld sample blade profiles. Blade profiles having varying thicknesses along the length of the profile were chosen.

Real blades obtained from the industry were welded upon to test the weld method and this was subsequently compared with a manually welded blade – repaired by an experienced welder – to showcase the advantages of automated welding using a robot when compared to manual welding.

- **COMPONENT BUILD-UP**

The initial steps for component build-up are similar to the steps involved in blade repair. The main difference is that in blade repair the heat input required is low and only a small amount of metal is deposited based on the required thickness. For component build-up the primary requirement is to deposit a much larger amount of metal and therefore a corresponding increase in the heat input. Managing this heat is of primary importance to prevent the base from warping. Warping not only destroys the base but also distorts the weld causing difficulties in depositing subsequent layers and gives rise to major defects as will be seen in the following chapter. Therefore to control the heat, experiments were conducted with a specially developed cooling fixture and base material of different dimensions and thicknesses to ascertain an easier and more suitable option. Multiple layers of welds were created to obtain rectangular blocks of pure weld metal from which tensile specimens were cut out. Tensile tests were conducted on these specimens.

This chapter on experimental techniques has presented basic information on the materials being used, robotic welding and the welding methods employed. The testing methods and equipment have also been discussed. With the knowledge of how the tests are conducted and the sequence in which they were conducted it is time to move on to the next chapter titled TESTING AND RESULTS.

IV – TESTING, RESULTS AND DISCUSSION

This chapter will discuss all the experiments in detail. The initial experiments, their outcome and how these lead to further experiments are discussed. The results of the experiments are analyzed. All approaches considered and their progress is highlighted in several places where appropriate.

4.1 PARAMETERS WHICH AFFECT DEPOSITION

During the literature review it was seen that there are several factors that affect metal deposition. While some of them affect the welding and deposition directly there are others which affect the process indirectly. After a detailed study of the literature the parameters which affect metal deposition have been tabulated as shown in Table 4.1.

VARIABLE PARAMETERS	VARIABLE PARAMETERS
VOLTAGE	WIRE MATERIAL
CURRENT	GAP BETWEEN ELECTRODES
TRAVEL SPEED	STEP OVER
WIRE FEED RATE	LAYER THICKNESS
SHIELDING GAS	PULSED CURRENT
HEAT INPUT	PULSE DURATION
SUBSTRATE TEMPERATURE	CURRENT RAMP-UP / RAMP-DOWN
TEMPERATURE B/W LAYERS	PRE-FLOW GAS TIME
DROPLET SIZE	POST-FLOW GAS TIME
POSITION AND ANGLE OF WELDING TORCH	FREQUENCY
DIA OF WELDING WIRE	ARC LENGTH
DEPOSITION ACCURACY	COOLING RATE

Table 4.1 – PARAMETERS WHICH AFFECT DEPOSITION

4.2. CRITICAL CONTROLLABLE PARAMETERS

Table 4.1 lists several parameters. It is not practically possible to consider all parameters at the same time. It was decided to first focus on the weld parameters which have the greatest influence on the quality of a weld. Some parameters have a greater effect than others and hence deemed as more important. Further, it was seen that some weld parameters have a direct effect on the welding process. Some of these parameters can be easily controlled as the weld parameters can be programmed into the robot and changes in any one of these parameters was seen to drastically affect the weld geometry and quality. Therefore it was decided to conduct experiments on those weld parameters which were decided as the critical controllable parameters. The critical controllable parameters are:

- WELDING CURRENT (Amps)
- VOLTAGE – in terms of ARC LENGTH (mm)
- TRAVEL SPEED (m/min)
- WIRE FEED RATE (m/min)

4.3. ESTABLISHING OPTIMAL PARAMETERS

For the given weld wire and base material, it was critical to first establish the optimal weld parameters to get a visually high quality weld before any of its mechanical properties could be evaluated. A good weld is one which has even, consistent and clean deposition of metal. It should have uniformity in width of the weld and height of the deposit and should be free of excessive ripples.

The experiments were conducted in a sequential manner by varying one weld parameter at a time and keeping all the other parameters constant. The welds were categorized based on their visual appearance to start with. The chosen weld parameters were used in the next set of experiments on which mechanical tests were conducted. Each of these experiments is dealt with in detail in the following sections.

4.4. BLADE REPAIR - INITIAL EXPERIMENTS

a. COUPON 1 – VARYING CURRENT – ARC LENGTH = 4 mm

Figure 4.1 – COUPON 1

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	30	4	0.6	0.13
2	40	4	0.6	0.13
3	50	4	0.6	0.13
4	55	4	0.6	0.13
5	60	4	0.6	0.13
6	65	4	0.6	0.13
7	70	4	0.6	0.13
8	80	4	0.6	0.13

Table 4.2 – WELD PARAMETERS – COUPON 1

In Table 4.2 it can be seen that the variable parameter is the CURRENT. The current has been varied across a broad spectrum from 30 A to 80 A. The corresponding welds can be seen in Figure 4.1. Note how the insufficient heat input at 30 A and 40 A causes weld beads and as the current is increased they join to form a more even pass. At 70 A the weld is a straight line of overlapping weld beads. The increase in current to 80 A causes an increase in width.

b. COUPON 2 – VARYING CURRENT – ARC LENGTH = 3 mm

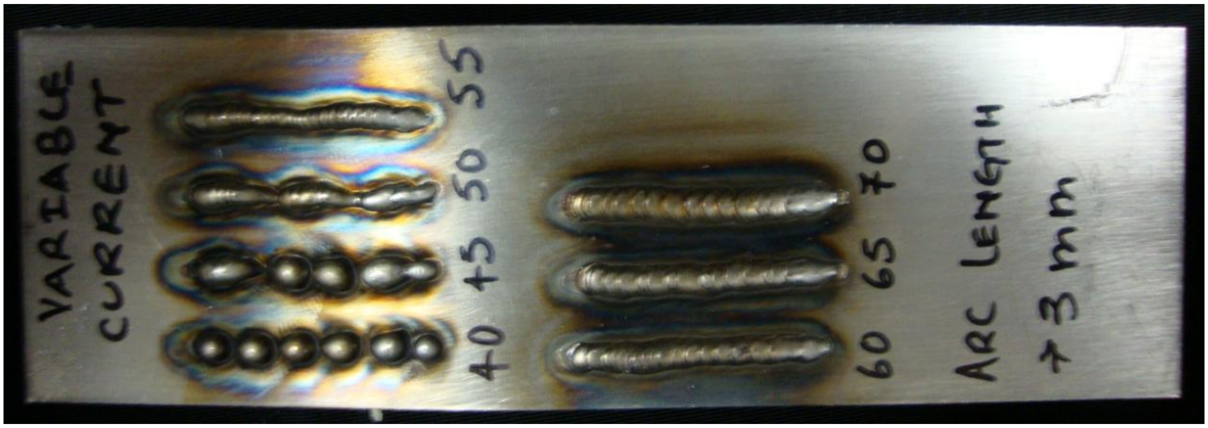


Figure 4.2 – COUPON 2

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	40	3	0.6	0.13
2	45	3	0.6	0.13
3	50	3	0.6	0.13
4	55	3	0.6	0.13
5	60	3	0.6	0.13
6	65	3	0.6	0.13
7	70	3	0.6	0.13

Table 4.3 – WELD PARAMETERS – COUPON 2

The same weld parameters have been used but with a reduction in ARC LENGTH to 3 mm. This reduction has resulted in a better quality weld at 60, 65 and 70 A when compared to an ARC LENGTH of 4 mm.

c. COUPON 3 – VARYING CURRENT AT 0.65 & 0.7 m/min WIRE FEED RATE

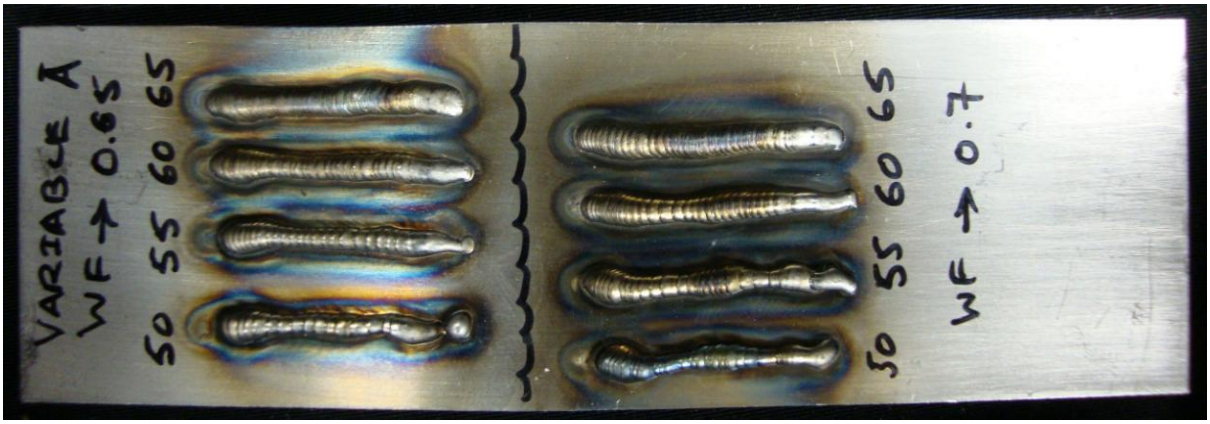


Figure 4.3 – COUPON 3

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	50	3	0.65	0.13
2	55	3	0.65	0.13
3	60	3	0.65	0.13
4	65	3	0.65	0.13

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	50	3	0.7	0.13
2	55	3	0.7	0.13
3	60	3	0.7	0.13
4	65	3	0.7	0.13

Table 4.4 – WELD PARAMETERS – COUPON 3

Figure 4.3 shows a comparison between two different WIRE FEED RATES (WF). It can be seen that the increase in WIRE FEED RATE increases the overlap between the weld beads. Therefore weld at 65 A and 0.7 WF is a more uniform weld than 65 A and 0.65 WF. From this it is clear that an optimal WIRE FEED RATE for that particular CURRENT will produce a near perfect weld in which the entire weld will look like a single rod or bar rather than a string of overlapping beads.

d. COUPON 4 – VERTICAL BUILD-UP – Z AXIS

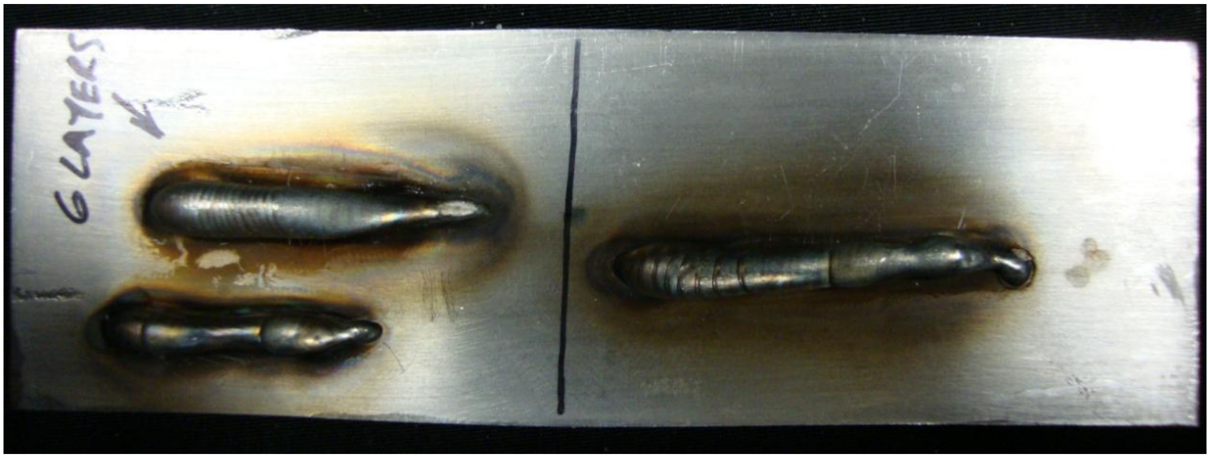


Figure 4.4 – COUPON 4

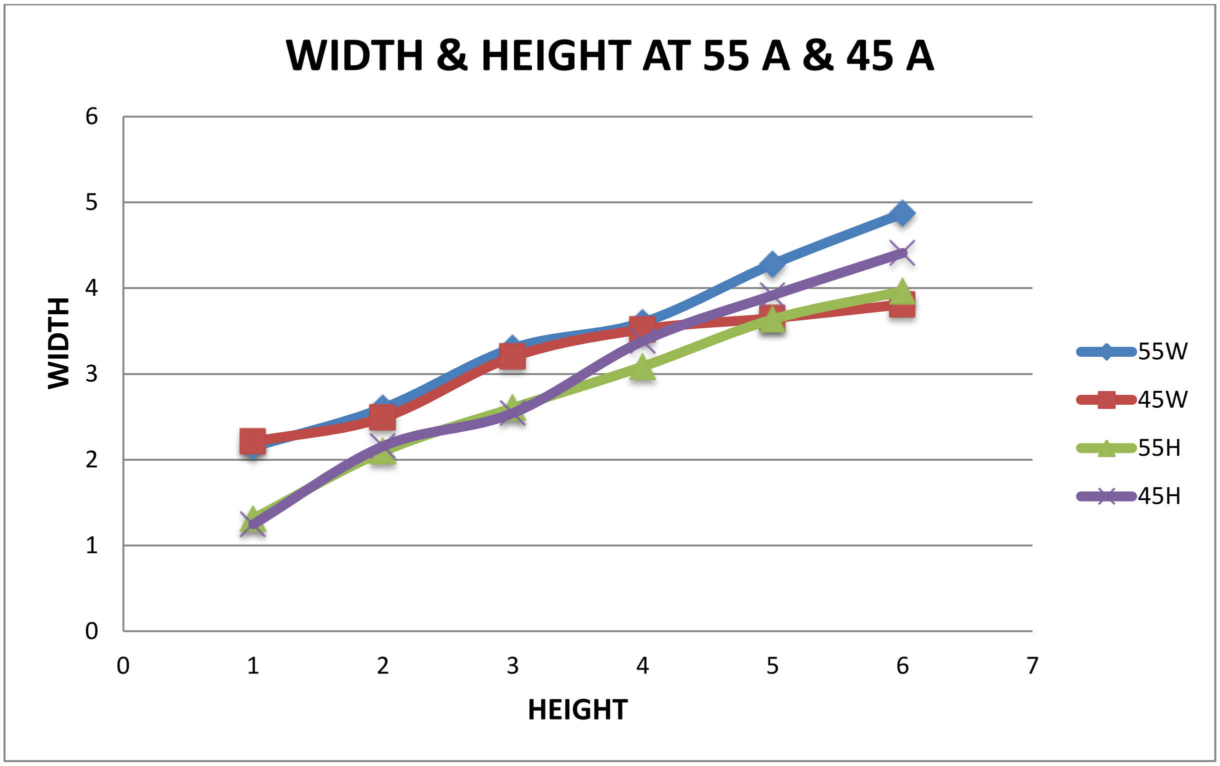
SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)	LAYERS	WIDTH (mm)	HEIGHT (mm)
1	55	3	0.6	0.13	1	2.15	1.31
2	55	3	0.6	0.13	2	2.6	2.10
3	55	3	0.6	0.13	3	3.3	2.60
4	55	3	0.6	0.13	4	3.6	3.09
5	55	3	0.6	0.13	5	4.28	3.64
6	55	3	0.6	0.13	6	4.87	3.96

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)	LAYERS	WIDTH (mm)	HEIGHT (mm)
1	45	3	0.6	0.13	1	2.21	1.25
2	45	3	0.6	0.13	2	2.49	2.16
3	45	3	0.6	0.13	3	3.2	2.54
4	45	3	0.6	0.13	4	3.52	3.38
5	45	3	0.6	0.13	5	3.65	3.92
6	45	3	0.6	0.13	6	3.81	4.41

Table 4.5 – WELD PARAMETERS – COUPON 4

In this test the parameters for a good weld from the previous test were used to make a vertical build-up of six layers. The CURRENT is the only variable in this test.

The last two columns show the width and height of the weld after each layer of metal has been deposited. A graph of WIDTH and HEIGHT at 55 A and 45 A is shown in Graph 4.1.



Graph 4.1 – WIDTH & HEIGHT AT 55 A & 45 A

From the graph it can be seen that at 55 A the width of the weld is wider and the height of metal deposited is lower than that at 45 A. Therefore an increase in CURRENT, even by 10 A causes a proportional increase in the heat input and the increased ability to melt the weld wire is the reason for a wider and lower weld. This difference in geometry is not confined to a single layer of deposited metal. The increased heat is also able to melt the base metal or the underlying layers in subsequent weld passes increasing the depth of penetration and thus also contributing to reduction in the height of the weld.

NOTE: It was also found that the heat retained by the underlying layers also plays a major role. During the above experiment layer on layer was deposited with no time to allow the weld to cool to room temperature. In section 4.8 the specimen was allowed to cool down to room temperature after every pass and the results can be seen in Figure 4.12.

4.5 EDGE BUILD-UP EXPERIMENTS

The next sets of experiments are intended to take one closer to the goal of rebuilding the edges of blades. The 3 mm edge was used to establish the initial weld parameters for edge build-up as the parameters will not be the same since the area of the base being welded is different. The weld parameters from the earlier tests as well as the knowledge gained from welding those samples were used as a reference to establish the weld parameters for edge build-up.

a. EDGE BUILD-UP – COUPON 10 – VARIABLE WIRE FEED RATE AT 35 A

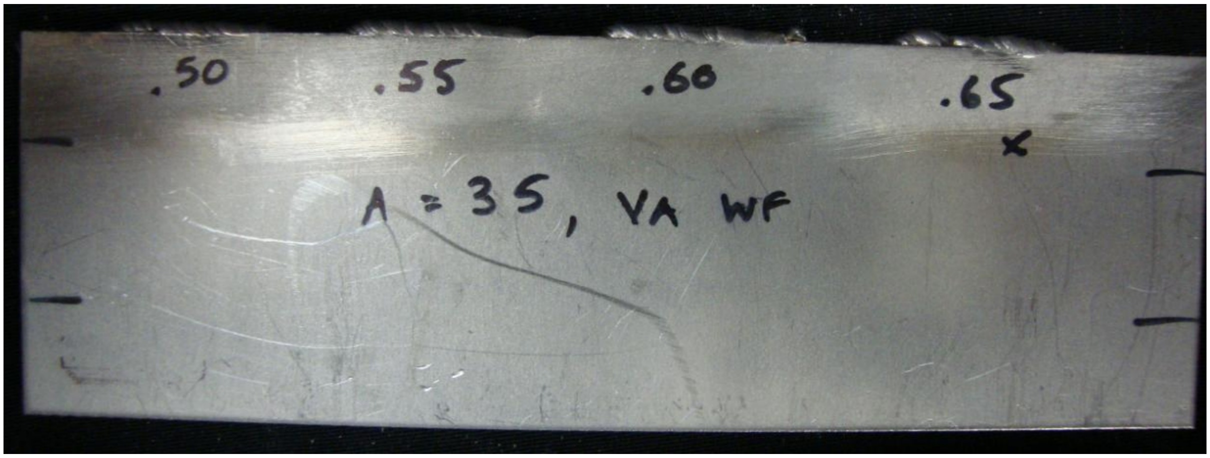


Figure 4.5 – COUPON 10

The weld parameters are shown in Table 4.6 on the following page. The variable parameter in this case is the WIRE FEED RATE (WF). As has been done before the aim of this experiment was to be able to create a weld of desired geometry and parameters were selected from the previous set of tests. These tests will help to further narrow down on the optimal parameters.

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	35	3	0.5	0.13
2	35	3	0.55	0.13
3	35	3	0.6	0.13
4	35	3	0.65	0.13

Table 4.6 – WELD PARAMETERS – COUPON 10

b. EDGE BUILD-UP – COUPON 9 – VARIABLE WIRE FEED RATE AT 40 A

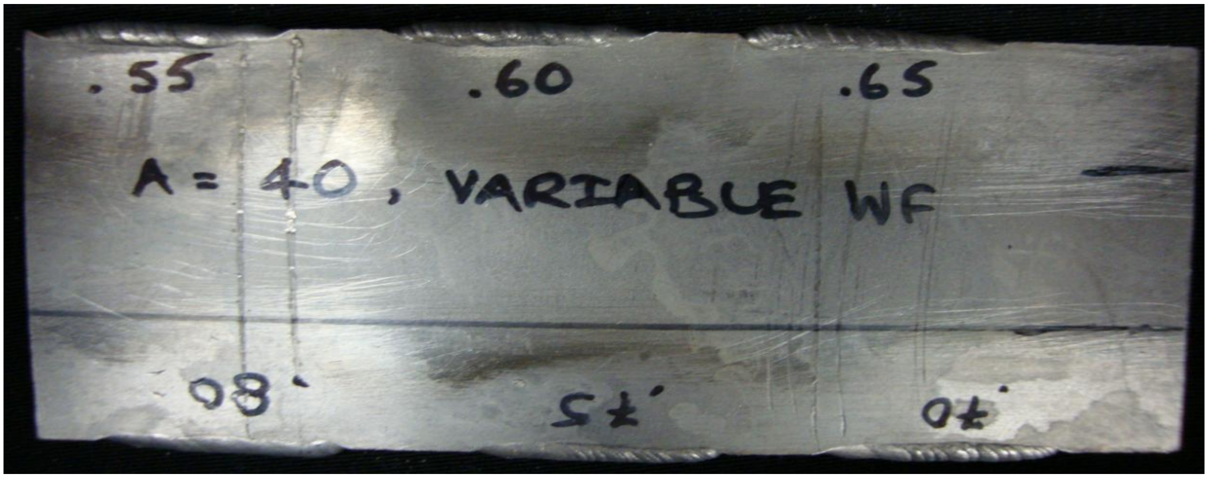


Figure 4.6 – COUPON 9

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	40	3	0.5	0.13
2	40	3	0.55	0.13
3	40	3	0.6	0.13
4	40	3	0.65	0.13
1	40	3	0.7	0.13
2	40	3	0.75	0.13
3	40	3	0.8	0.13
4	40	3	0.85	0.13

Table 4.7 – WELD PARAMETERS – COUPON 9

c. EDGE BUILD-UP – COUPON 12 – VARIABLE WIRE FEED RATE AT 45 A

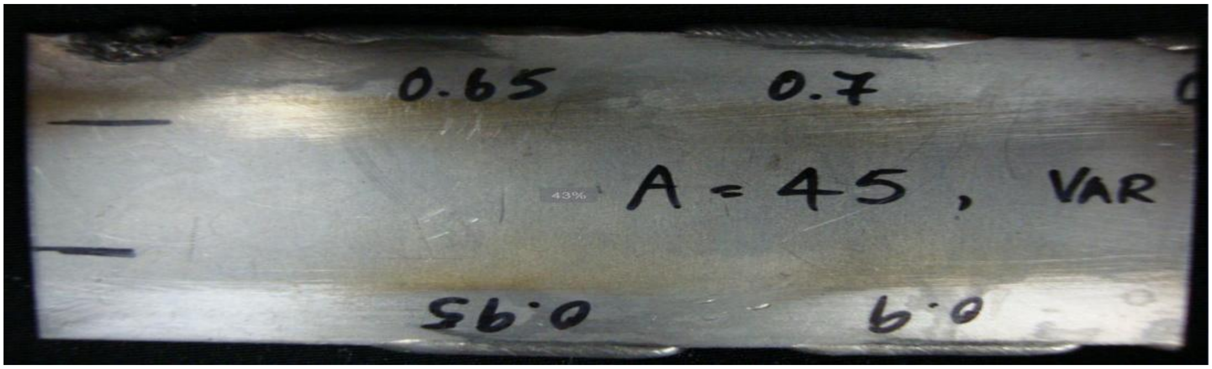


Figure 4.7 – COUPON 12

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	45	3	0.65	0.13
2	45	3	0.7	0.13
3	45	3	0.7	0.13
4	45	3	0.75	0.13
1	45	3	0.8	0.13
2	45	3	0.85	0.13
3	45	3	0.9	0.13
4	45	3	0.95	0.13

Table 4.8 – WELD PARAMETERS – COUPON 12

d. EDGE BUILD-UP – COUPON 13 – VARIABLE WIRE FEED RATE AT 50 A & 55 A

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	50	3	0.65	0.13
2	50	3	0.7	0.13
3	50	3	0.7	0.13
4	50	3	0.75	0.13
1	50	3	0.8	0.13
2	50	3	0.85	0.13
3	50	3	0.9	0.13
4	50	3	0.95	0.13

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	55	3	0.7	0.13
2	55	3	0.75	0.13
3	55	3	0.8	0.13
4	55	3	0.85	0.13

Table 4.9 & 4.10 – WELD PARAMETERS – COUPON 13

4.6. MICRO HARDNESS TEST

In the experiments conducted several good welds were produced but these could only be evaluated qualitatively. It was therefore necessary to find a way to differentiate between welds quantitatively. Micro hardness tests were performed on cross sections of the weld samples.

To perform the micro hardness tests in a systematic manner three weld sections were selected. The only variable between the three weld sections was the CURRENT, 40, 45 and 50 A respectively. It was decided that the results would provide more insight if there were two sets of samples being tested. The first set consisting of three weld samples of each of the three different welds were mounted in Bakelite and tested directly whereas the second set also consisting of three weld samples of the three different welds were first heat treated at 1175 degrees Celsius before mounting and then their micro hardness measurements were taken.

a. MICRO HARDNESS TEST – BEFORE HEAT TREATMENT – VARYING CURRENT

Table 4.11 (a), (b) & (c) show the hardness test results of the two sets of samples corresponding to their respective CURRENT values. The final column shows the average value of the two samples for each set. These averaged readings were used to compare the mechanical property of the weld – in this case the effect of CURRENT on the MICRO HARDNESS of the WELD SECTION.

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS HV		AVG HARDNESS-HV
				1	2	
1	40	300	0	186	182	184
2	40	300	0.25	182	179	181
3	40	300	0.5	190	185	188
4	40	300	0.75	188	191	190
5	40	300	1	184	185	185
6	40	300	1.25	186	185	186
7	40	300	1.5	188	177	183
8	40	300	1.75	192	169	181
9	40	300	2	186	172	179
10	40	300	2.25	183	172	178
11	40	300	2.5	176	179	178
12	40	300	2.75	192	165	179
13	40	300	3	195	175	185
14	40	300	3.25	180	185	183
15	40	300	3.5	197	169	183

Table 4.11 (a) – MICRO HARDNESS – CURRENT 40 A

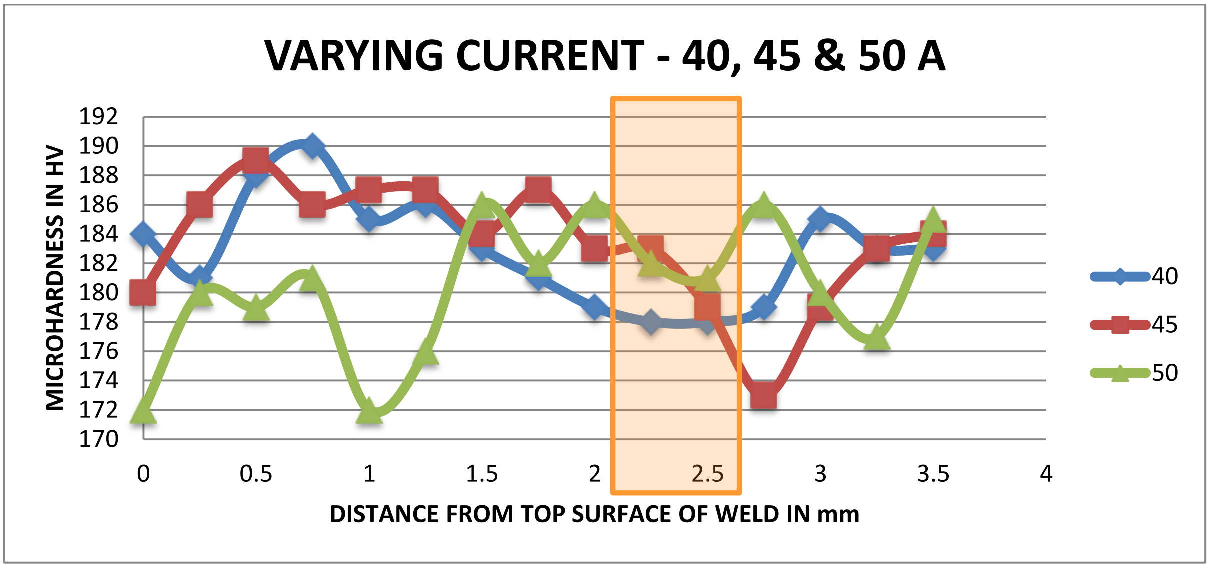
SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS HV		AVG HARDNESS-HV
				1	2	
1	45	300	0	180	179	180
2	45	300	0.25	179	193	186
3	45	300	0.5	195	182	189
4	45	300	0.75	192	180	186
5	45	300	1	195	179	187
6	45	300	1.25	191	183	187
7	45	300	1.5	187	181	184
8	45	300	1.75	198	176	187
9	45	300	2	184	181	183
10	45	300	2.25	188	177	183
11	45	300	2.5	176	181	179
12	45	300	2.75	174	172	173
13	45	300	3	177	181	179
14	45	300	3.25	197	168	183
15	45	300	3.5	180	188	184

Table 4.11 (b) – MICRO HARDNESS – CURRENT 45 A

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV		AVG HARDNESS-HV
				1	2	
1	50	300	0	175	168	172
2	50	300	0.25	178	181	180
3	50	300	0.5	184	173	179
4	50	300	0.75	179	182	181
5	50	300	1	168	176	172
6	50	300	1.25	178	173	176
7	50	300	1.5	213	159	186
8	50	300	1.75	185	179	182
9	50	300	2	199	172	186
10	50	300	2.25	192	172	182
11	50	300	2.5	194	168	181
12	50	300	2.75	196	175	186
13	50	300	3	192	167	180
14	50	300	3.25	188	165	177
15	50	300	3.5	194	175	185

Table 4.11 (c) – MICRO HARDNESS – CURRENT 50 A

A graph of the average hardness values is plotted versus the distance from the top of the weld as shown in Graph 4.2



Graph 4.2 – COMPARISON OF MICRO HARDNESS AT 40, 45 & 50 A

Theoretically it is known that the hardness decreases with increase in heat input. The increase in current directly increases the heat input to the area. In the graph the weld at 40 A has a hardness much higher than 45 A and 50 A at the tip of the weld.

HEAT INPUT = (VI / S) x 60 J - Equation 1

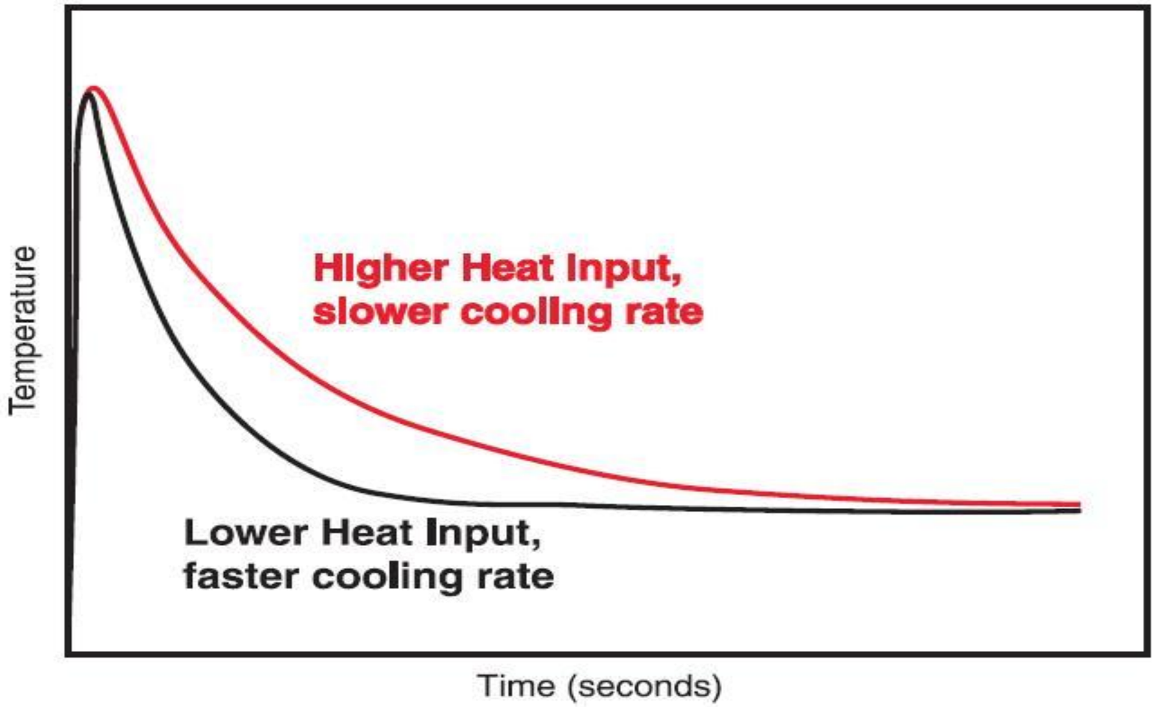
Where,

V = Voltage in volts

I = Current in Amps

S = Travel speed in m/min

From equation 1 it can be seen that HEAT INPUT is directly proportional to the CURRENT. Therefore an increase in the current increases the heat input thereby resulting in reduced hardness values. As we move towards the intersection of the weld with the base material we can see that the hardness values are much closer to each other.



Graph 4.3 – INFLUENCE OF HEAT INPUT ON COOLING RATE [30]

Higher heat inputs result in slower cooling rates as shown in Graph 4.3. Slower cooling rates tend to soften the material and hence reduce the micro hardness values.

b. MICRO HARDNESS TEST – HEAT TREATED – VARYING CURRENT

Table 4.12 (a), (b) & (c) show the hardness test results of the 3 sets of HEAT TREATED samples corresponding to their respective CURRENT values. The final column shows the average value of the 3 samples for each set. These averaged readings were used to compare the mechanical property of the weld – in this case the effect of CURRENT on the MICRO HARDNESS of the WELD SECTION.

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	40	300	0	159	168	155	161
2	40	300	0.25	156	164	160	160
3	40	300	0.5	169	161	168	166
4	40	300	0.75	174	154	169	166
5	40	300	1	179	161	166	169
6	40	300	1.25	185	151	160	165
7	40	300	1.5	200	158	164	174
8	40	300	1.75	183	147	158	163
9	40	300	2	174	161	149	161
10	40	300	2.25	168	141	160	156
11	40	300	2.5	168	153	157	159
12	40	300	2.75	165	177	151	164
13	40	300	3	175	159	167	167
14	40	300	3.25	177	183	149	170
15	40	300	3.5	197	156	150	168

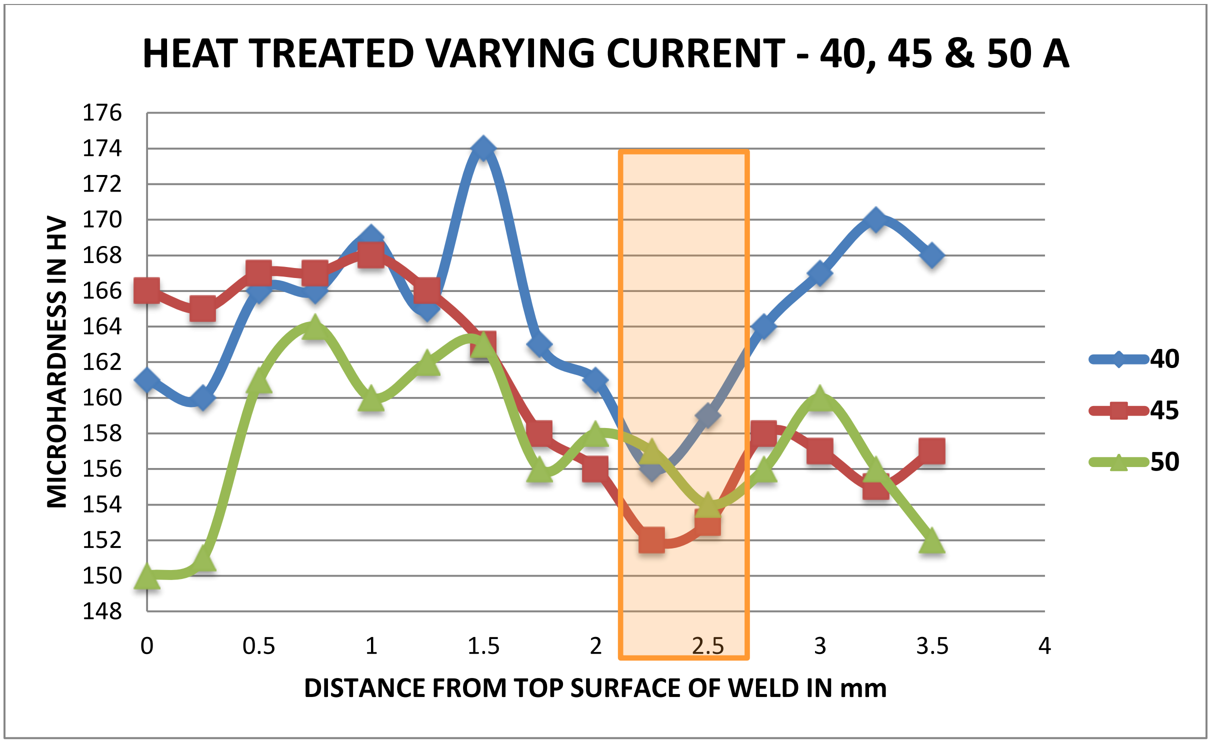
Table 4.12 (a) – MICRO HARDNESS HT – CURRENT 40 A

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	45	300	0	164	152	181	166
2	45	300	0.25	162	162	171	165
3	45	300	0.5	159	170	172	167
4	45	300	0.75	164	172	166	167
5	45	300	1	164	170	171	168
6	45	300	1.25	161	171	166	166
7	45	300	1.5	151	172	167	163
8	45	300	1.75	149	165	160	158
9	45	300	2	151	147	171	156
10	45	300	2.25	147	155	155	152
11	45	300	2.5	153	144	161	153
12	45	300	2.75	144	156	173	158
13	45	300	3	156	156	158	157
14	45	300	3.25	146	163	155	155
15	45	300	3.5	154	149	169	157

Table 4.12 (b) – MICRO HARDNESS – CURRENT 45 A

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	50	300	0	151	143	155	150
2	50	300	0.25	150	149	155	151
3	50	300	0.5	168	156	158	161
4	50	300	0.75	167	168	158	164
5	50	300	1	166	160	155	160
6	50	300	1.25	163	168	155	162
7	50	300	1.5	163	165	160	163
8	50	300	1.75	145	162	162	156
9	50	300	2	156	158	159	158
10	50	300	2.25	155	159	158	157
11	50	300	2.5	148	167	147	154
12	50	300	2.75	160	162	147	156
13	50	300	3	154	165	161	160
14	50	300	3.25	140	158	170	156
15	50	300	3.5	159	142	156	152

Table 4.12 (c) – MICRO HARDNESS – CURRENT 50 A



Graph 4.4 – COMPARISON OF MICRO HARDNESS HT SAMPLES AT 40, 45 & 50 A

From the graph it can be seen that the hardness values decrease upon heat treatment. Similar to the earlier graph the hardness values at the interface are closer to each other. As seen in Equation 1 HEAT INPUT is directly proportional to CURRENT. Therefore increase in current increases the heat input.

NOTE:

- It has to be noted that the change in CURRENT is in relatively small 5 A increments. Visually and geometrically acceptable welds could not be obtained with a larger difference in CURRENT.
- The graph appears scattered mainly because the range used is very small and is in increments of 2 HV.

c. MICRO HARDNESS TEST – BEFORE HEAT TREATMENT – VARYING TRAVEL SPEED

Table 4.13 (a), (b) & (c) show the hardness test results of the two sets of samples corresponding to their respective TRAVEL SPEED values. The final column shows the average value of the two samples for each set. These averaged readings were used to compare the mechanical property of the weld – in this case the effect of TRAVEL SPEED on the MICRO HARDNESS of the WELD SECTION.

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV		AVG HARDNESS-HV
				1	2	
1	40	300	0	186	182	184
2	40	300	0.25	182	179	181
3	40	300	0.5	190	185	188
4	40	300	0.75	188	191	190
5	40	300	1	184	185	185
6	40	300	1.25	186	185	186
7	40	300	1.5	188	177	183
8	40	300	1.75	192	169	181
9	40	300	2	186	172	179
10	40	300	2.25	183	172	178
11	40	300	2.5	176	179	178
12	40	300	2.75	192	165	179
13	40	300	3	195	175	185
14	40	300	3.25	180	185	183
15	40	300	3.5	197	169	183

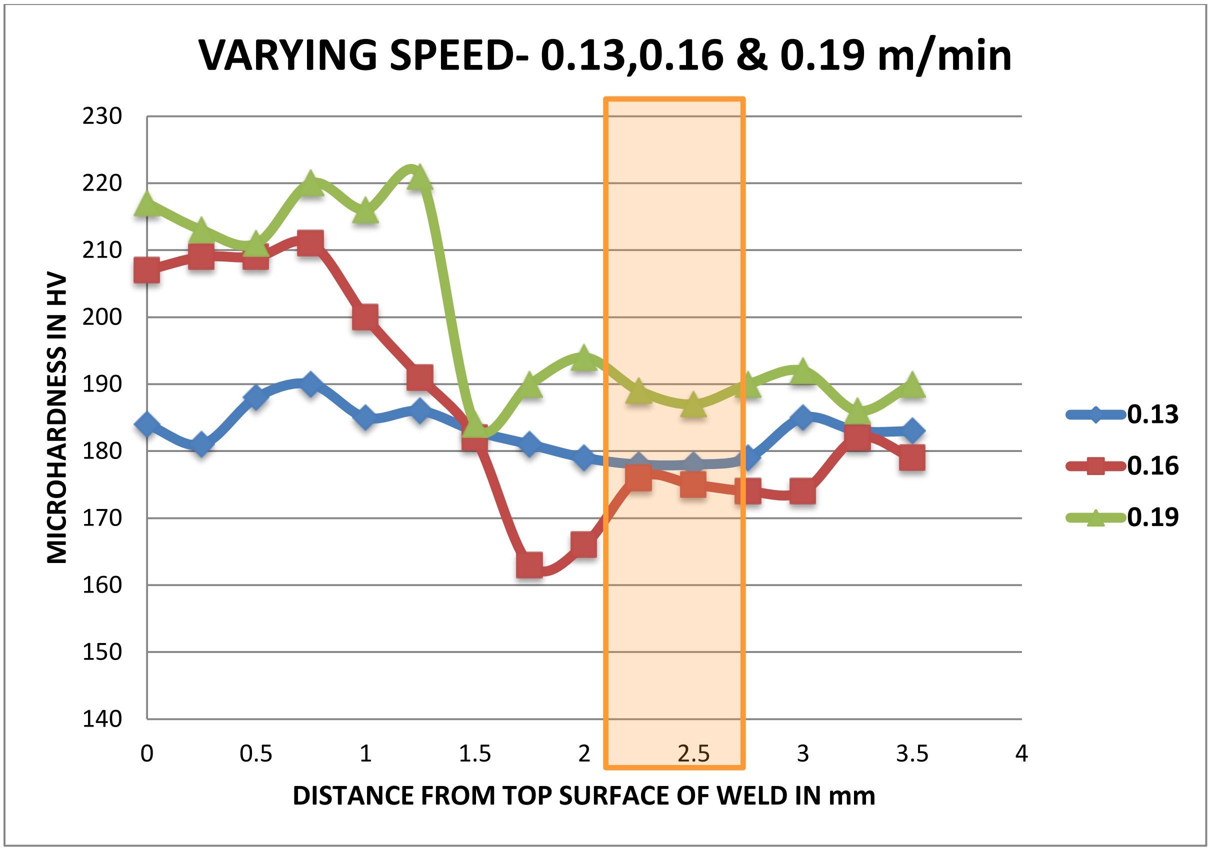
Table 4.13 (a) – MICRO HARDNESS – SPEED 0.13 m/min

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV		AVG HARDNESS-HV
				1	2	
1	40	300	0	207	206	207
2	40	300	0.25	212	205	209
3	40	300	0.5	205	212	209
4	40	300	0.75	211	210	211
5	40	300	1	187	213	200
6	40	300	1.25	174	208	191
7	40	300	1.5	172	192	182
8	40	300	1.75	172	154	163
9	40	300	2	159	173	166
10	40	300	2.25	175	176	176
11	40	300	2.5	177	173	175
12	40	300	2.75	172	175	174
13	40	300	3	179	169	174
14	40	300	3.25	186	178	182
15	40	300	3.5	170	187	179

Table 4.13 (b) – MICRO HARDNESS – SPEED 0.16 m/min

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV		AVG HARDNESS-HV
				1	2	
1	40	300	0	221	213	217
2	40	300	0.25	215	211	213
3	40	300	0.5	210	211	211
4	40	300	0.75	221	218	220
5	40	300	1	213	218	216
6	40	300	1.25	226	215	221
7	40	300	1.5	175	192	184
8	40	300	1.75	185	195	190
9	40	300	2	187	201	194
10	40	300	2.25	198	180	189
11	40	300	2.5	180	194	187
12	40	300	2.75	185	194	190
13	40	300	3	181	203	192
14	40	300	3.25	175	197	186
15	40	300	3.5	178	202	190

Table 4.13 (c) – MICRO HARDNESS – SPEED 0.19 m/min



Graph 4.5 – COMPARISON OF MICRO HARDNESS AT 0.13, 0.16 & 0.19 m/min

Theoretically we know that increase in heat input reduces the hardness of the weld. Increase in TRAVEL SPEED is indirectly proportional to the HEAT INPUT. The hardness value of the tip of the weld at 0.19 m/min is much higher than the hardness values at 0.16 m/min and 0.13 m/min.

Again from equation 1 HEAT INPUT is inversely proportional to TRAVEL SPEED. Hence increase in travel speed reduces the heat input. Reduced heat input corresponds to faster cooling rates. Therefore with increase in TRAVEL SPEED the material HARDNESS increases.

d. MICRO HARDNESS TEST – HEAT TREATED – VARYING TRAVEL SPEED

Table 4.14 (a), (b) & (c) show the hardness test results of the three sets of HEAT TREATED samples corresponding to their respective TRAVEL SPEED values. The final column shows the average value of the three samples for each set. These averaged readings were used to compare the mechanical property of the weld – in this case the effect of TRAVEL SPEED on the MICRO HARDNESS of the WELD SECTION.

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	40	300	0	159	168	155	161
2	40	300	0.25	156	164	160	160
3	40	300	0.5	169	161	168	166
4	40	300	0.75	174	154	169	166
5	40	300	1	179	161	166	169
6	40	300	1.25	185	151	160	165
7	40	300	1.5	200	158	164	174
8	40	300	1.75	183	147	158	163
9	40	300	2	174	161	149	161
10	40	300	2.25	168	141	160	156
11	40	300	2.5	168	153	157	159
12	40	300	2.75	165	177	151	164
13	40	300	3	175	159	167	167
14	40	300	3.25	177	183	149	170
15	40	300	3.5	197	156	150	168

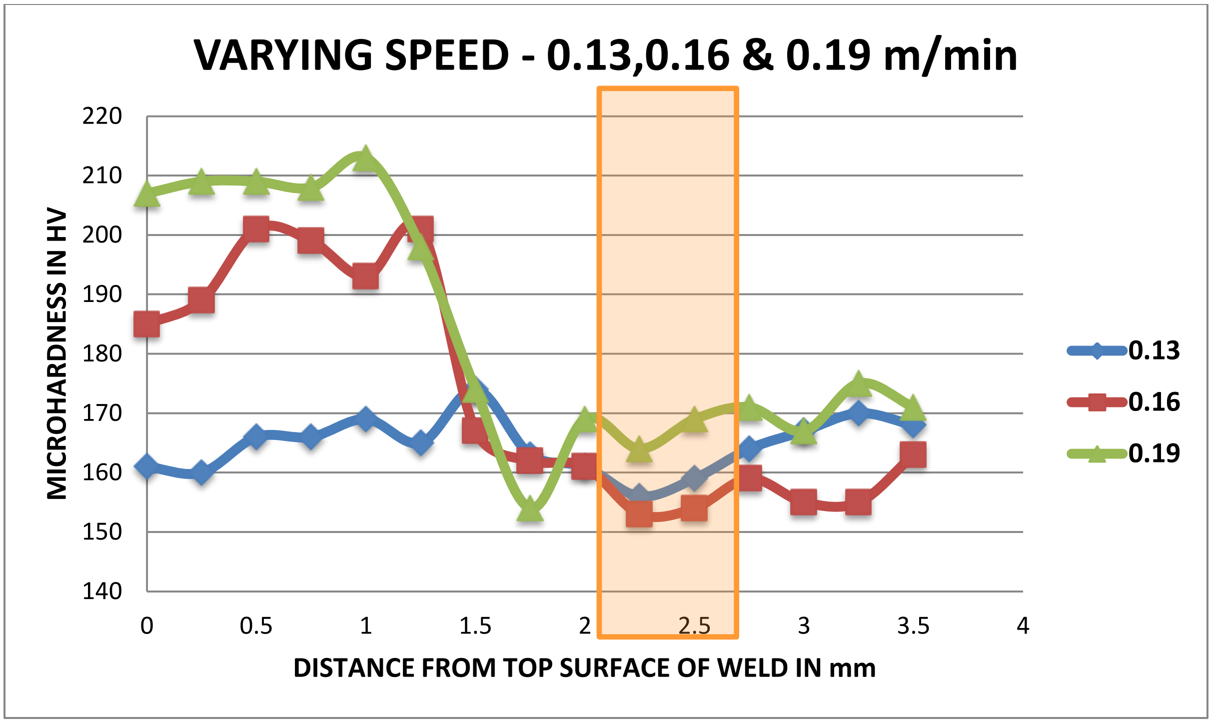
Table 4.14 (a) – MICRO HARDNESS HT – SPEED 0.13 m/min

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	40	300	0	179	190	186	185
2	40	300	0.25	191	182	193	189
3	40	300	0.5	211	201	192	201
4	40	300	0.75	208	206	183	199
5	40	300	1	195	203	182	193
6	40	300	1.25	208	193	203	201
7	40	300	1.5	181	164	157	167
8	40	300	1.75	169	156	162	162
9	40	300	2	169	160	153	161
10	40	300	2.25	150	164	144	153
11	40	300	2.5	148	161	154	154
12	40	300	2.75	155	157	164	159
13	40	300	3	143	164	158	155
14	40	300	3.25	144	150	170	155
15	40	300	3.5	161	175	152	163

Table 4.14 (b) – MICRO HARDNESS – SPEED 0.16 m/min

SL No	CURRENT A	LOAD g	DEPTH mm	HARDNESS-HV			AVG HARDNESS-HV
				1	2	3	
1	40	300	0	206	215	199	207
2	40	300	0.25	211	211	205	209
3	40	300	0.5	208	210	208	209
4	40	300	0.75	212	210	202	208
5	40	300	1	221	217	201	213
6	40	300	1.25	203	198	194	198
7	40	300	1.5	166	185	170	174
8	40	300	1.75	150	168	145	154
9	40	300	2	166	192	149	169
10	40	300	2.25	160	177	155	164
11	40	300	2.5	159	188	161	169
12	40	300	2.75	175	174	165	171
13	40	300	3	175	169	157	167
14	40	300	3.25	172	182	171	175
15	40	300	3.5	178	182	154	171

Table 4.14 (c) – MICRO HARDNESS – SPEED 0.19 m/min



Graph 4.6 – COMPARISON OF MICRO HARDNESS HT SAMPLES AT 0.13, 0.16 & 0.19 m/min

From the graph it can be seen that the hardness values decrease upon heat treatment. Increase in TRAVEL SPEED is indirectly proportional to the HEAT INPUT. The hardness value of the tip of the weld at 0.19 m/min is much higher that the hardness values at 0.16 m/min and 0.13 m/min. From equation 1 HEAT INPUT is inversely proportional to TRAVEL SPEED. Hence increase in travel speed reduces the heat input. Reduced heat input corresponds to faster cooling rates. Therefore with increase in TRAVEL SPEED the material HARDNESS increases.

4.7. EDGE BUILD-UP OF THIN WALLS WITH DIFFERENT THICKNESS

In the previous section we have dealt with samples having a constant thickness of 3 mm. It is important to note that edge build-up of blade profiles are much more complicated as they involve cross sections having varying thickness along the profile. Therefore to be able to rebuild the edges of blades it is necessary to establish weld parameters to obtain welds of different widths. This knowledge can then be applied to weld blade profiles that have varying cross sections.

The standard sample of 3 mm thickness was rolled down to samples having thickness 1, 1.5, 2 and 2.5 mm respectively. Welding along a straight line was carried out on these edges to establish the weld parameters required to obtain suitable welds on each one of these edges.

a. EDGE BUILD-UP OF THIN WALLS – 2.5 mm

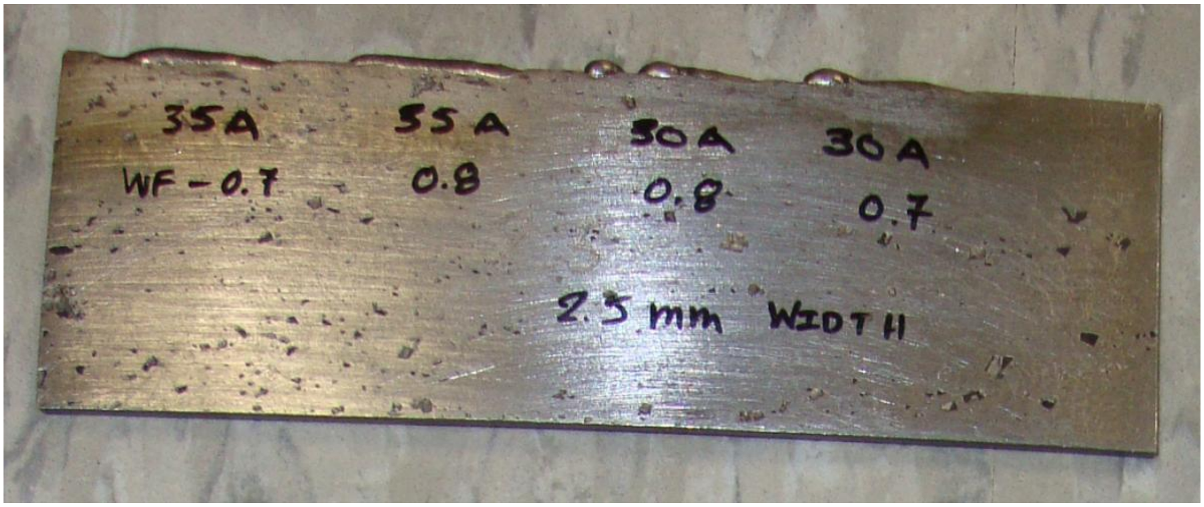


Figure 4.8 – EDGE BUILD-UP 2.5 mm

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	35	3	0.7	0.13
2	35	3	0.8	0.13
3	30	3	0.8	0.13
4	30	3	0.7	0.13

Table 4.15 – EDGE BUILD-UP – 2.5 mm

b. EDGE BUILD-UP OF THIN WALLS – 2 mm

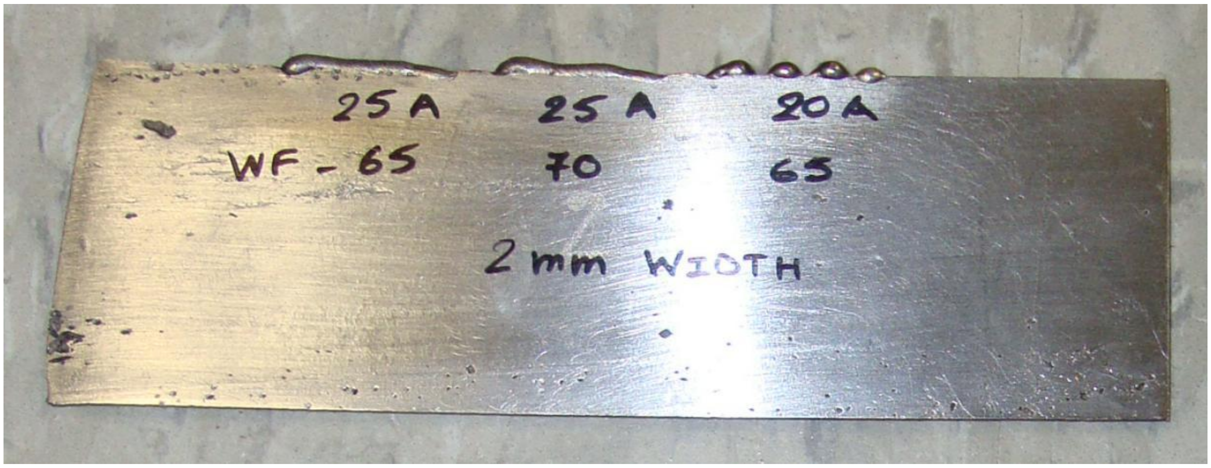


Figure 4.9 – EDGE BUILD-UP 2 mm

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	25	3	0.65	0.13
2	25	3	0.7	0.13
3	20	3	0.65	0.13

Table 4.16 – EDGE BUILD-UP – 2 mm

c. EDGE BUILD-UP OF THIN WALLS – 1.5 mm

Figure 4.10 – EDGE BUILD-UP 1.5 mm

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	15	3	0.5	0.13
2	20	3	0.5	0.13
3	20	3	0.6	0.13
4	20	3	0.65	0.13

Table 4.17 – EDGE BUILD-UP – 1.5 mm

d. EDGE BUILD-UP OF THIN WALLS – 1 mm

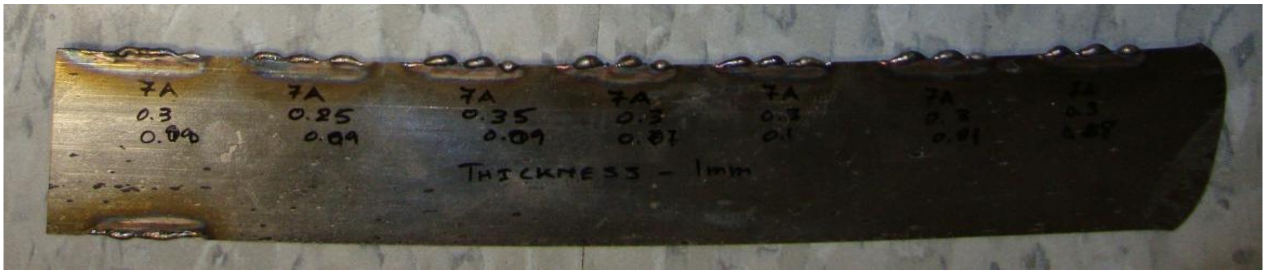


Figure 4.11 – EDGE BUILD-UP 1 mm

In Figure 4.11 we can see that the weld is not uniform and is in the form of weld beads when welding with a higher current. Since the edge is extremely thin the arc causes the edge to melt before metal can be deposited. It was barely possible to obtain an acceptable weld with a current of 7 A and wire feed of 0.3 m/min at a reduced travel speed of 0.08 m/min

e. EDGE BUILD-UP OF THIN WALLS – OPTIMAL PARAMETERS

After keen observation of the edge build-up one set of parameters was chosen for each edge thickness based on the uniformity and geometry of the weld. The Table of optimal weld parameters for each thickness is shown in Table 4.18.

SL No	THICKNESS	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)
1	1	7	3	0.3	0.08
2	1.5	20	3	0.65	0.13
3	2	25	3	0.65	0.13
4	2.5	35	3	0.8	0.13
5	3	40	3	0.85	0.13

Table 4.18 – OPTIMAL WELD PARAMETERS FOR DIFFERENT EDGE THICKNESS

4.8. EDGE BUILD-UP – MULTIPLE LAYER THIN WALL

This section involves the creation of a multiple layered thin wall. A thin wall 3 mm wide – same as the base material – and of 10 mm height was created. The parameters used are the same as that obtained earlier for 3 mm thickness. Successive welds were deposited layer by layer. After each layer the distance between the electrode and the previous layer was reset to 3 mm.

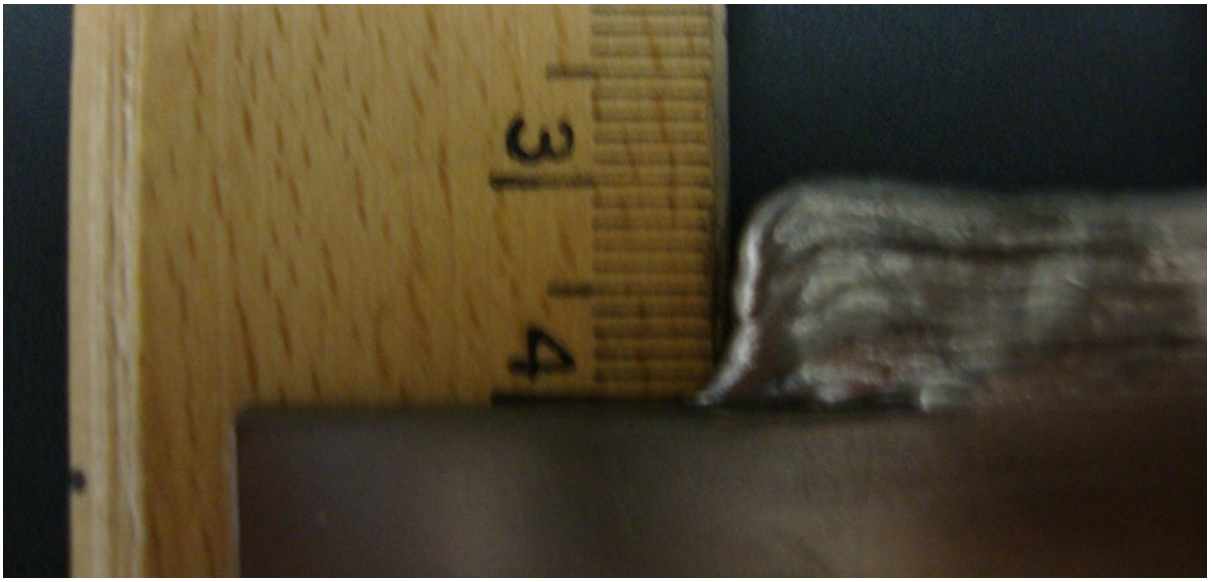
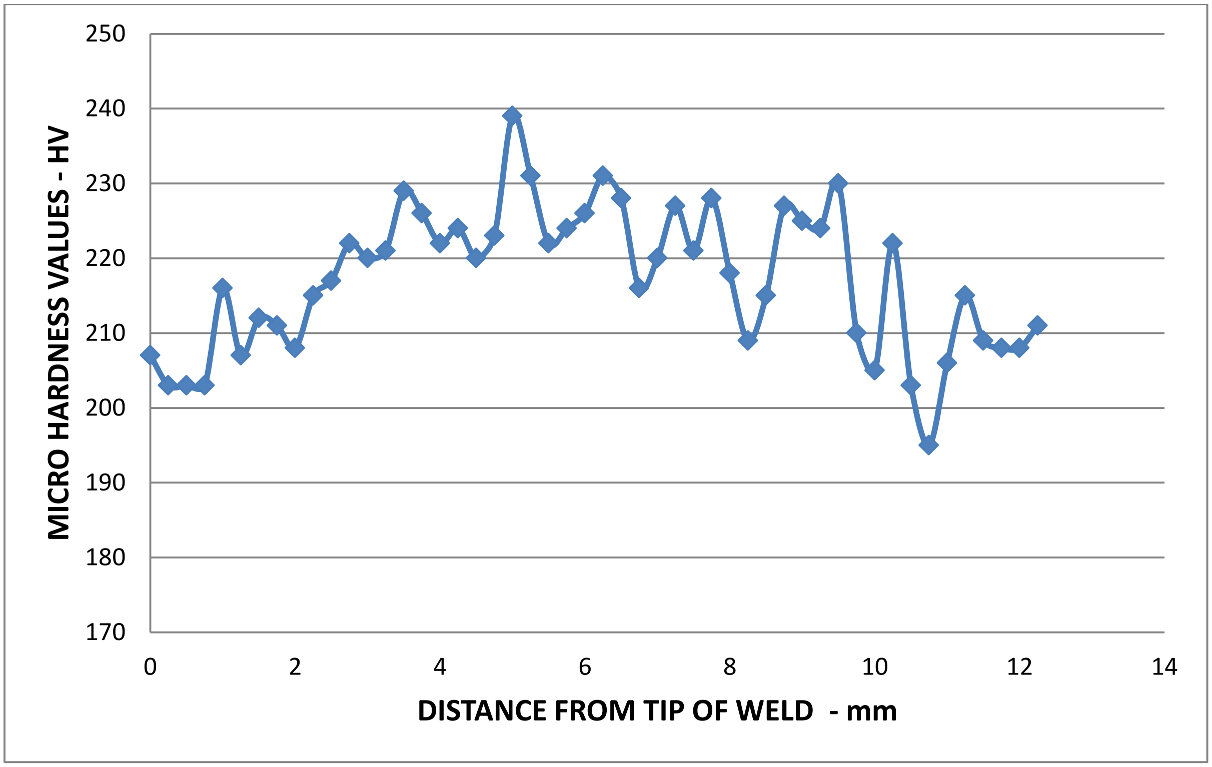


Figure 4.12 – THIN WALL 10 mm IN HEIGHT

Ten successive layers were required to create the wall of 10 mm height. Initial attempts at creating the wall failed. As new layers were deposited on the underlying layers they tend to be wider than the one below causing a 'mushrooming' effect because of which the wall no longer maintains a uniform width and desired height. Over several attempts it was found that better results were obtained when the time interval between each pass was increased. The heat retained by the underlying layers as well as the base material was the primary reason behind increased width of the upper layers of the wall.

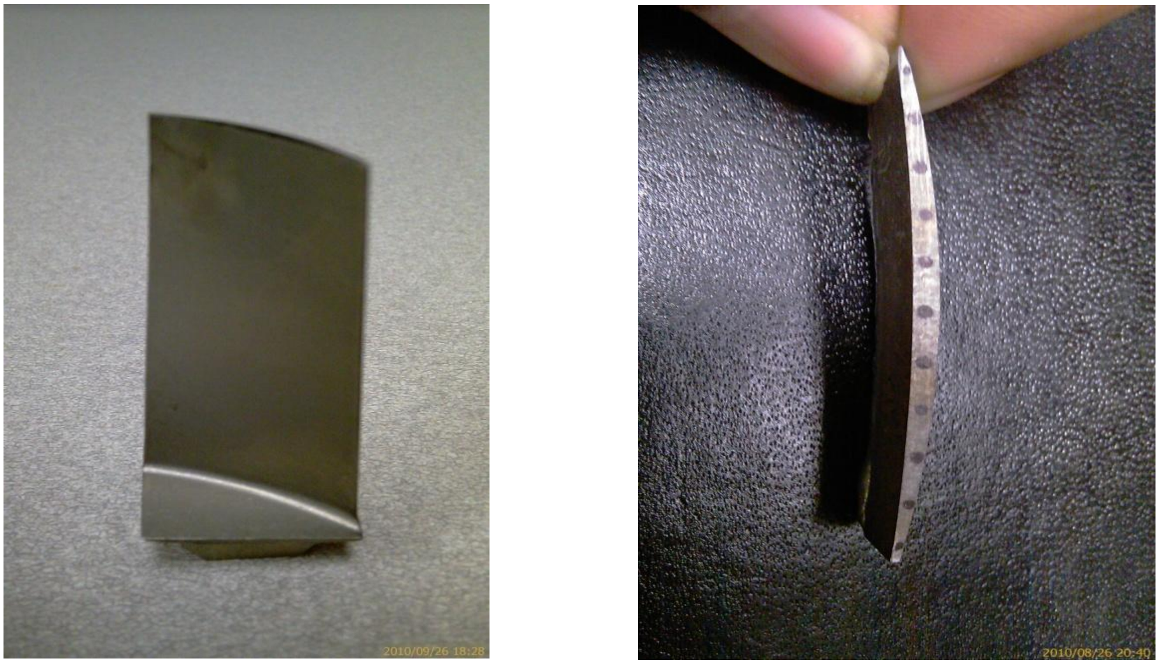
In the sample shown in Figure 4.12 the sample was allowed to cool down to room temperature after every weld pass. A wall having uniform thickness along its height was obtained. Each weld pass is an individual layer and the layers can be easily distinguished from each other. A cross section of the above sample was made and its micro hardness values recorded as before.



Graph 4.7 – MICRO HARDNESS VALUES 10 mm WALL

4.9. BLADE WELDING – VARYING CROSS SECTION

To demonstrate robotic welding on a gas turbine blade, a blade with varying cross section along the profile was selected - FIG 4.13 (a). The blade profile was cut out of a rectangular slab of Inconel 718 – Figure 4.13 (b).



)

(a) (b)

Figure 4.13 – SELECTED BLADE & BLADE PROFILE FOR WELDING

The selected profile has a varying cross section and therefore the same weld parameters cannot be used to weld the complete profile. Instead the blade can be divided into several points depending on the change in thickness. In Figure 4.13 (b) the points are marked on the profile.

The welding strategy is to program weld parameters into the robot depending on the thickness at that particular point. The weld parameters are obtained from Table 4.18 which contains the optimal parameters derived from welding on edges having different thicknesses.

During the welding operation the robot will apply the programmed welding parameters as it arrives at each point. The change in weld parameters will cater to the change in thickness of the blade profile producing a weld of desired quality.

Figure 4.14 – BLADE PROFILE AFTER DEPOSITION OF A LAYER OF METAL

Figure 4.14 shows the completed weld on the blade profile. The change in weld parameters at various points on the profile controlled the heat input and ensured that only the desired amount of metal was deposited at any given point on the profile.

It took several samples to achieve this level of weld quality. The main problem was the inability to strike the arc at the tip of the profile due to insufficient thickness. The tip of the blade is a point and on several occasions the arc would melt the edge before it could weld on it. The solution was to strike the arc at a small distance away from the tip where there was sufficient width.

4.10. COMPONENT BUILD-UP – INITIAL EXPERIMENTS

The main difference between BLADE REPAIR and COMPONENT BUILD-UP is the amount of metal deposited. Blade repair is a more delicate process in which every effort is made to achieve accurate dimensions and outstanding weld quality. The weld parameters are tailored to the material being used as well as the profile of that particular blade. The amount of heat input is of utmost importance as excessive heat can adversely affect the mechanical properties of the weld. Component build-up on the other hand involves the deposition of increased amounts of metal. The metal is deposited as weld passes, layer on layer to form a near net shape of the final object being manufactured. However it is still important to control the heat as well as limit the amount of metal deposited to achieve the desired quality and finish.

As discussed in CHAPTER 3, every component built will be a combination of overlapping horizontal and vertical weld passes. The overlap between each weld pass ensures that there are no holes or voids and is critical in maintaining a flat surface which will then act as the base for the next layer. The overlap can be input into the robot as an OFFSET and this offset needs to be calculated based on the width of the weld being produced by the weld parameters being used.

4.11. OFFSET OF 2 mm AND 4 mm

Table 4.19 shows the parameters used in welding the two samples shown in Figure 4.15. It can be seen from the Table that the weld parameters, especially the weld current is still close to that being used for edge build-up. The weld passes were of good visual quality as individual welds but since they are narrow and high it was very difficult to obtain a perfect overlap of two layers.

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)	LAYERS	STEP O (mm)
1	55	3	0.6	0.13	1	2
2	55	3	0.6	0.13	1	4

Tables 4.19 – SINGLE LAYER WELDS WITH OFFSET – 2 mm & 4 mm

Theoretically a small offset should ensure a proper overlap but the height of the weld in comparison to its width poses a major problem. When the robot tries to place the second pass at a desired offset from the first pass the height of the previous pass causes the robot to strike an arc with the previous weld which is closer to it than the base and therefore causes mixing of welds as shown in Figure 4.15.

Figure 4.15 – SINGLE LAYER WITH OFFSET 2 mm & 4 mm BETWEEN PASSES

4.12. MULTIPLE LAYER BUILD-UP

The CURRENT was increased to obtain a weld which was much wider than the ones obtained in the previous test. The cross section of this weld is not a sharp bump as in the previous test. It is a smooth curve and hence does not pose the problem of striking an arc with the previous pass. Figure 4.16 (a) shows a six layer weld and its weld parameters are shown in Table 4.20.

(a) (b)

Figure 4.16 – MULTIPLE LAYER BUILD-UP

SL No	CURRENT (Amps)	ARC LENGTH (mm)	WIRE FEED (m/min)	TRAVEL SPEED (m/min)	LAYERS	STEP O (mm)
1	75	3	0.9	0.13	1	4

Table 4.20 – WELD PARAMETERS – MULTIPLE LAYER BUILD-UP

Figure 4.16 (b) shows the warping effects on the 3 mm plate due to the high heat. The warping causes complete distortion of the base and the first few layers. The unevenness caused also affects the upper layers. As the base starts to warp the surface is no longer flat and hence while depositing a new weld pass there is a chance of striking the arc with an adjacent weld pass thus causing a gap to be formed where the original weld should have been. If this gap is not filled by the weld pass of the next layer then it will form a void as shown in Figure 4.16 (a).

Figure 4.17 – 25 mm THICK BASE AFTER WELDING AND EDM

After experimenting with the cooling fixture described in chapter three, it was found out that the use of thicker base material is a simpler solution as the weld and base will be separated after completion of welding. As a result, the thin 3 mm strips were replaced with slabs of Inconel 718 which were 25 mm in thickness. There was negligible or no warpage in these slabs. One such slab is shown in Figure 4.17. In this figure the weld has been cut out already using the EDM.

4.13 COMPONENT BUILD-UP & TENSILE TESTING

After optimizing the weld parameters for multiple layer build-up the next step was to build a multiple layer rectangular block for making tensile samples. The tensile samples provide a method to evaluate the metal RP technique as well as analyze the mechanical properties. The expectation was to make a completely dense part which has no gaps or voids. The mechanical properties of the part produced must be comparable to the standard properties of the metal or alloy. Table 4.21 shows the weld parameters used for build-up of the tensile samples.

SL No	**CURRENT (Amps)**	**ARC LENGTH (mm)**	**WIRE FEED (m/min)**	**TRAVEL SPEED (m/min)**	**LAYERS**	**STEP O (mm)**
1	115	3	1	0.13	7	4

Table 4.21 – SINGLE LAYER – 10 PASSES

Figure 4.18 shows a single layer of deposited metal. The layer is made up of ten weld passes.

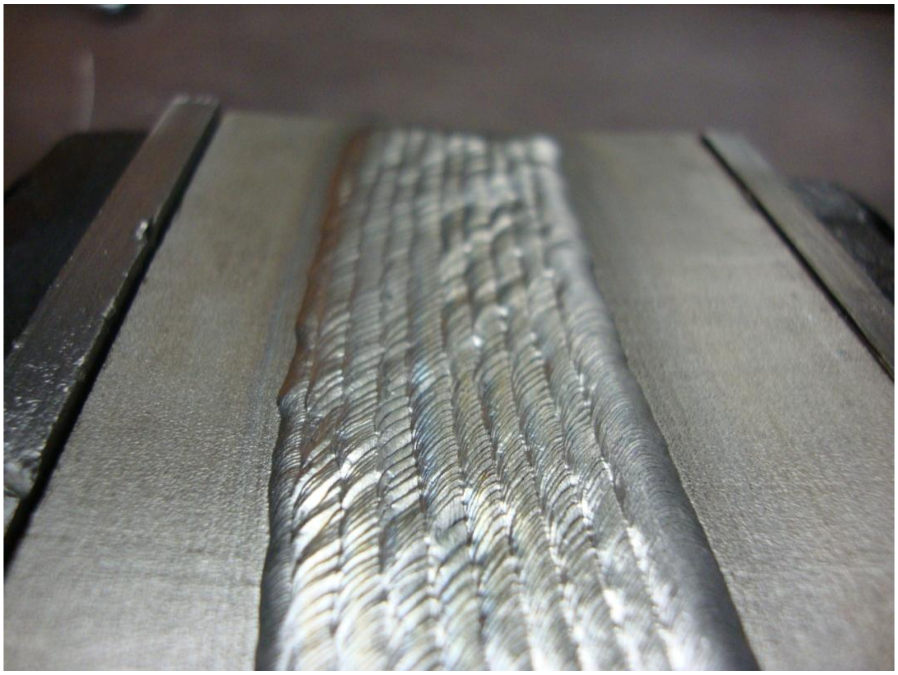


Figure 4.18 – SINGLE LAYER 10 PASSES

Each layer is similar to the one shown in the figure. The layers are deposited one on top of the other to finally achieve the required thickness. Figure 4.19 shows the completed weld with seven layers.

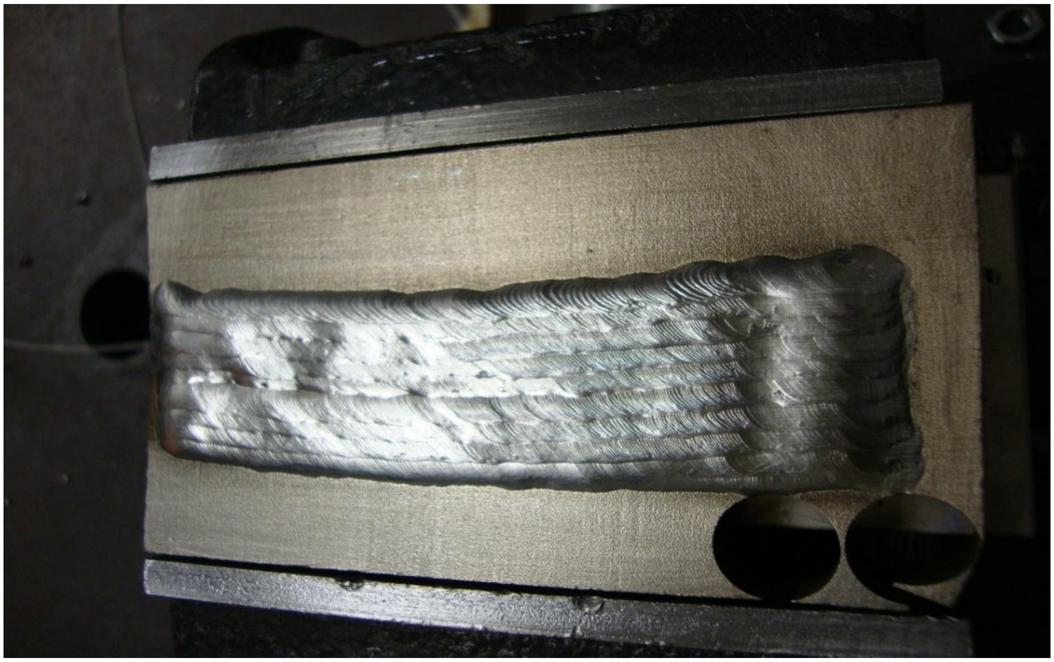


Figure 4.19 – RECTANGULAR WELD BLOCK

The weld is then cut using the electric discharge machine (EDM) to obtain the tensile test specimen shown in Figure 4.20.

Figure 4.20 – TENSILE TEST SPECIMEN

One such tensile sample was cut in the longitudinal and transverse directions. The cut samples were mounted in Bakelite and polished. The samples (Figure 4.21) were then etched using Oxalic acid and observed under the binocular microscope to reveal the different layers and their alignment. The samples are approximately 80mm x 25mm. The figure shown is not to scale.

Figure 4.21 – LONGITUDINAL & TRANSVERSE SECTIONS

- LONGITUDINAL SECTION

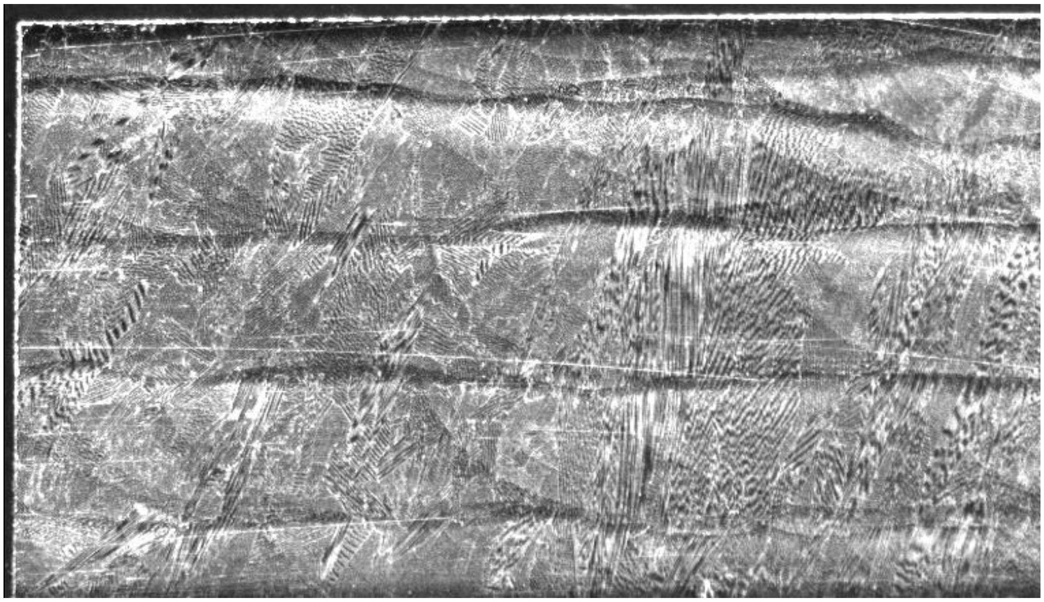


Figure 4.22 – LONGITUDINAL SECTION SHOWING DIFFERENT LAYERS

In Figure 4.22 the different layers can be easily identified. Since the tensile test specimen was cut from the rectangular block using the EDM half layers can be seen at the bottom and the top of the figure.

- TRANSVERSE SECTION

Figure 4.23 shows the microscopic image of the transverse section in which different weld passes in each layer can be easily identified. The way the layers overlap each other can be related to the way description of the RP methodology builds the material as stated in the previous Chapter.

Figure 4.23 – TRANSVERSE SECTION – WELD PASSES & LAYERS

SAMPLE No	LOAD kg	CROSS HEAD SPEED mm/min	CHART SPEED mm/min
1	3000	0.5	20
2	3000	0.5	10
3	3000	0.5	10

Table 4.22 – INSTRON SETTINGS

The tensile samples were tested on the INSTRON. The test parameters are shown in Table 4.22.

4.14 TENSILE TEST

a. SAMPLE 01

Table 4.23 shows the measurements of the tensile sample and the average cross sectional area. The sample gauge length is 20mm. Cross sectional area of the sample is 26.7 mm^2

SL No	WIDTH mm	DEPTH mm
1	5.38	5
2	5.36	4.96
3	5.3	5.01

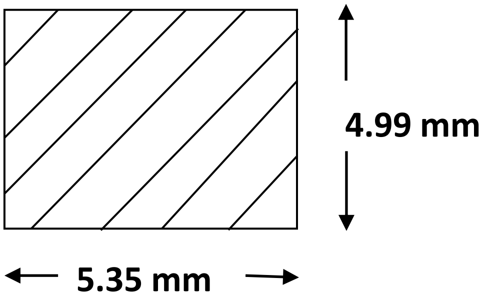


Table 4.23 – CROSSECTIONAL AREA – SAMPLE 01

Full scale of 3000 kg is represented by 250 mm on the graph. The graph obtained is similar to the one shown in Figure 3.20.

Therefore 1mm is 12 kg

- **YIELD STRESS**

Point of intersection of 0.2% offset line = 82 mm

(82 x 12)/26.7 x 9.81 = 361.54 Mpa

- **ULTIMATE TENSILE STRENGTH**

Highest point on the graph = 150 mm

150 x 12 = 1800 kg

Therefore UTS = (1800 / 26.7) x 9.81 = 661.35 Mpa

- **STRAIN**

Initial length of markings on the sample = 23.68 mm

Final length after testing = 28.8 mm

Change in Length = 5.12 mm

Strain = Change in Length / original length = 5.12/23.68 = 0.216 = 22 %

b. SAMPLE 02

Table 4.24 shows the measurements of the tensile sample and the average cross sectional area. The sample gauge length is 20mm. Cross sectional area of the sample is 31.28 mm^2

SL No	WIDTH mm	DEPTH mm
1	5.46	5.74
2	5.43	5.75
3	5.43	5.75

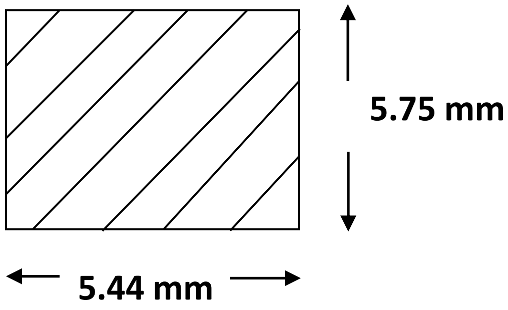


Table 4.24 – CROSSECTIONAL AREA – SAMPLE 02

Full scale of 3000 kg is represented by 250 mm on the graph.

Therefore 1mm is 12 kg

- **YIELD STRESS**

Point of intersection of 0.2% offset line = 91 mm

(91 x 12)/31.28 x 9.81 = 342.47 Mpa

- **ULTIMATE TENSILE STRENGTH**

Highest point on the graph = 150 mm

150 x 12 = 1800 kg

Therefore UTS = (1800 / 31.28) x 9.81 = 564.51 Mpa

- **STRAIN**

Initial length of markings on the sample = 22.96 mm

Final length after testing = 27.26 mm

Change in Length = 4.3 mm

Strain = Change in Length / original length = 4.3/22.96 = 0.187 = 19 %

c. SAMPLE 03

Table 4.25 shows the measurements of the tensile sample and the average cross sectional area. The sample gauge length is 20mm. Cross sectional area of the sample is 35.04 mm^2

SL No	WIDTH mm	DEPTH mm
1	5.39	6.49
2	5.39	6.5
3	5.39	6.51

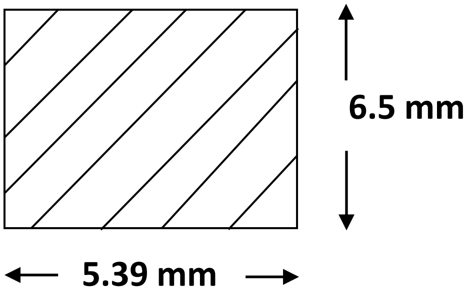


Table 4.25 – CROSSECTIONAL AREA – SAMPLE 03

Full scale of 3000 kg is represented by 250 mm on the graph.

Therefore 1mm is 12 kg

- **YIELD STRESS**

Point of intersection of 0.2% offset line = 100 mm

(100 x 12) / 35.04 x 9.81 = 335.96 Mpa

- **ULTIMATE TENSILE STRENGTH**

Highest point on the graph = 150 mm

140 x 12 = 1680 kg

Therefore UTS = (1680 / 35.04) x 9.81 = 470.34 Mpa

- **STRAIN**

Initial length of markings on the sample = 23.19 mm

Final length after testing = 26.41 mm

Change in Length = 3.22 mm

Strain = Change in Length / original length = 3.22/23.19 = 0.138 = 14 %

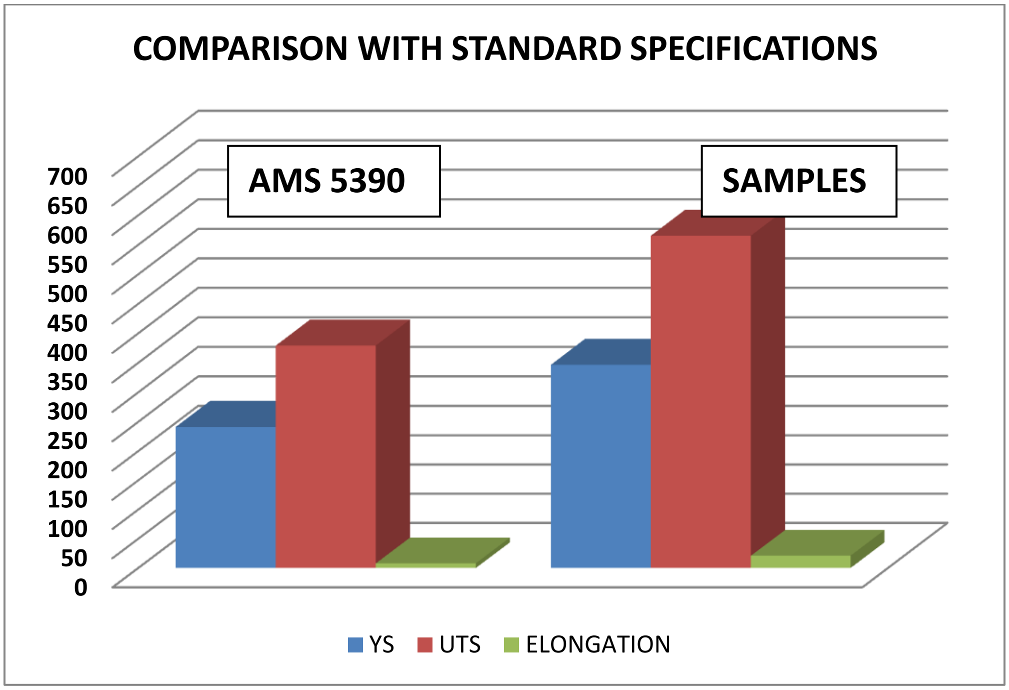
4.15 COMPARISON WITH STANDARD SPECIFICATIONS

The minimum specifications of alloy X according to the cast specifications of the alloy given by AMS 5390 are compared with the results obtained from the tensile samples. Table 4.26 compares the Yield stress, UTS and elongation.

PROPERTY	**AMS 5390**	**SAMPLE 01**	**SAMPLE 02**	**SAMPLE 03**
YIELD STRESS Mpa	242	362	343	336
UTS Mpa	379	661	565	470
% ELONGATION	8% min	22%	19%	14%

Table 4.26 – COMPARISON WITH STANDARD SPECIFICATIONS

From the Table it can be seen that the individual values obtained by testing the 3 samples are much higher than the standard specification. The average values of the yield stress, UTS and percentage elongation are plotted against the standard specification in Graph 4.8.



Graph 4.8 – AMS 5390 vs WELD SAMPLES

4.16 SMALL COMPONENT MANUFACTURE - EXAMPLE

This section will demonstrate the ability to manufacture a small component by robotic welding. The first step was to create the 3D model. Next the model was divided into layers of 1 mm each. Figure 4.24 shows the 3D model of the part. Figure 4.25 shows the first layer which consists of several weld passes. The weld parameters used were the same as those used for the tensile samples. The base of the part was built using linear weld passes and for the rectangular walls the robot was programmed to deposit metal in two L – shaped passes which meet at each end to form a rectangle.

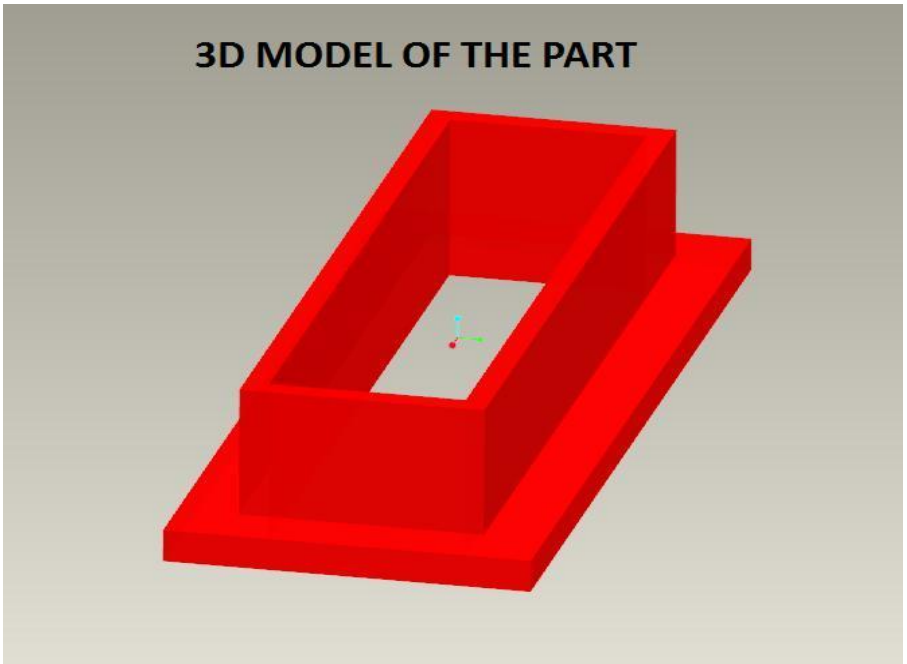


Figure 4.24 – 3D MODEL OF THE PART

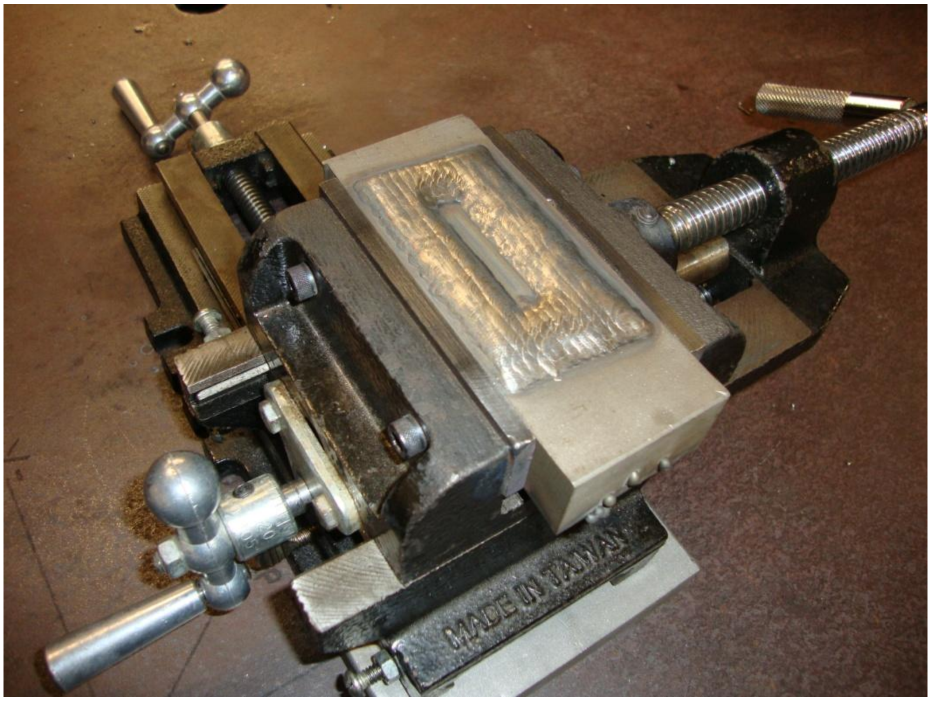


Figure 4.25 – DEPOSITION OF THE FIRST LAYER

Figure 4.26 – PART – AFTER WELDING

Figure 4.27 – FINAL MACHINED PART

Figure 4.26 shows the final part after welding. The part was machined using the EDM which offers limited flexibility. The inner pocket could not be machined with the EDM as it uses a continuous wire for cutting. The machined part is shown in Figure 4.27. The purpose of fabricating this part is to demonstrate that a small part can be built using robotic welding based metal rapid prototyping. Robots have a great degree of dexterity and path control ability. Hence the proposed method shows promise for fabricating small parts with greater details.

4.17 COST OF AUTOMATION

Automating a manual process is advantageous is several ways. It increases the productivity, improves quality, reduces the amount of rejections, provides a very high level of consistency and improves worker safety. Automation however comes at a cost. It involves substantial initial investment. Investment can be in the form of equipment, related jigs and fixtures, work shop modifications and operator training. Therefore it is necessary to analyze the cost involved as the ultimate aim is to cut costs and increase the profit margin.

- MANUAL Vs AUTOMATED BLADE REPAIR EXAMPLE

Consider a typical blade repair process as shown in Figure 4.28. The different workstations are, Pre- repair inspection and measurement, cut / grind and surface preparation, pre – weld inspection and amount of metal build – up, welding followed by Machining / polishing and finally post – repair inspection and approval. For this analysis only welding is taken into consideration assuming all the other stations are common to both manual and automated blade repair. Table 4.27 shows the cost comparison between manual welding and automated welding. The values are only for comparison and do not consider several factors such as number of welders, number of shifts, volume of blades and continuous operation of the robot.

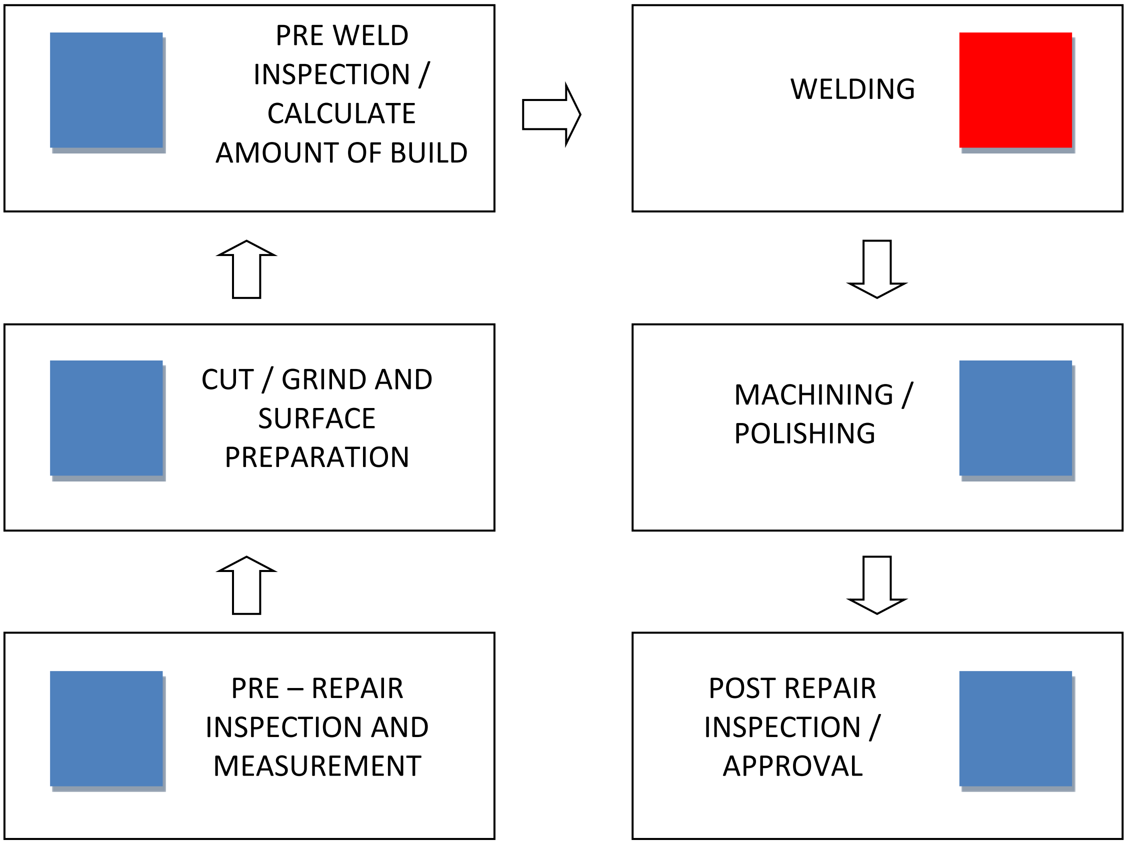


Figure 4.28 – SEQUENCE OF BLADE REPAIR STATIONS

PARAMETER	**MANUAL**	**AUTOMATED**	**COMMENTS**
LABOR COST	60 $/hr	15 $/hr	SkilledVs unskilled
TIME FOR 1 BLADE	1 m	15 s	Robot welding several blades on a fixture
100 blades x 50 Engines 5000 blades	$ 5000	$ 313	Savings of $ 4687

Table 4.27 – COST COMPARISON – MANUAL Vs AUTOMATED WELDING

If the initial cost of the robot is $ 70000 then the robot will have to weld 74,675 blades before the company can break even. Again this is subjective as the numbers indicated here are only for the sake of comparison. A detailed study of the manual welding process and robot welding times and associated costs will be required to get an accurate result.

Following are some of the scenarios when automation can be a success:

- Constant and high work volume will ensure that the robot is utilized to its full capability.
- A welding robot such as the one used for this research work is highly versatile and can be used for several other welding operations in addition to blade repair.
- Well established industries usually have such welding robots which can be programmed for repair work thereby eliminating the initial investment.
- The example shown only took blade repair into consideration, for component build – up the margins will be much higher as fabricating parts using welding as a rapid prototyping technique will eliminate the need for expensive moulds and dies.
- The high quality of parts, lower rejection rates and minimal scrap will indirectly Influence the cost benefit associated with automated welding.

This chapter discussed the various experiments and tests that were conducted. With regards to blade repair, first the weld parameters were optimized to obtain visually acceptable welds. Weld parameter optimization was then continued on thin edges of different thicknesses. Micro hardness testing was done on several samples with varying parameters. Using this knowledge a table was formed with optimized weld parameters which were used to weld the blade cross section.

Similarly for component build up the first step was to optimize the weld parameters. After optimizing the weld parameter, the next step was to make multiple layer build ups. Heat management issues were tackled. Tensile samples and a sample part were built using the RP techniques. Tensile testing was done to evaluate the mechanical properties of the part produced.

V - CONCLUSION & FUTURE WORK

This research work has shown the advantages of automated robotic welding. The repair and reconstruction of gas turbine blades by robotic welding was discussed and experiments and tests were conducted. On the basis of this research and the literature reviewed automated welding produces welds of high quality, high consistency, very high repeatability and offers higher productivity when compared to manual welding. In the second part of the research work welding was shown as a rapid prototyping technique to produce functional metal parts. Robotic welding was compared to traditional rapid prototyping techniques and was shown as a simple, comparatively inexpensive RP system.

5.1 BLADE REPAIR

- The research previously conducted in this area was reviewed and parameters which affect metal deposition were studied. Critical parameters were identified and experiments conducted by sequentially varying these parameters. Current, voltage, wire feed rate and travel speed were varied until the optimal setting was obtained for each of them.
- Optimized weld parameters were also developed for edges having different thicknesses. With these parameters welds of exact geometry were produced when needed. While welding the blade with varying cross section these parameters were very helpful in ensuring that only the right amount of heat sufficient to melt the wire was applied based on the thickness at that point.
- While welding the blades with varying cross section difficulties were encountered while welding the edge which is usually pointed and has a thickness of less than 0.5 mm. In such cases MELTDOWN with only the welding arc was first performed before welding.

The other method to overcome this problem was to slightly offset the arc start point such that there is sufficient thickness to strike the arc.

- A 10 layer weld sample was built to demonstrate the ability to fabricate thin walls and sections which can be used for reconstructing blades. Heat management in the underlying layers was important to ensure that each weld layer is of the same thickness as the one below.

5.2 WELDING AS A METAL RP TECHNIQUE

- In this research it has been shown that welding can be used as a RP technique for producing simple metal parts. The same methodology used to produce the tensile samples can be used to produce functional parts.
- Multiple weld passes with an optimal offset value between passes were used to make each layer of weld. Each layer was a slice of the overall part being fabricated. In this way several layers were deposited one on top of the other to form the part. Controlled metal deposition was achieved by optimizing the weld parameters.
- The robot is a versatile, comparatively inexpensive and more user friendly setup for RP when compared to stand alone systems and retro fitted CNC machines discussed in the literature. The robot comes with the proven capability as a welder and includes its own programming software and thus eliminates the need to develop custom software.

5.3 EVALUATION & TESTING

- Initial optimization was done based on the visual appearance of the weld. The next step was to assess the weld geometry. Cross sections of the weld samples were made and observed under the optical microscope. A uniform and fully dense weld was obtained which was free from gaps and voids. This was especially important in the case of multiple layer build-ups as an optimal path was necessary to ensure that there are no gaps between passes.

- Micro hardness testing was employed as the method to evaluate the edge build-up. A systematic approach was employed to evaluate the micro hardness of samples before heat treatment and after heat treatment. Based on the weld parameter the two groups were further divided into two.
- The first set had samples with varying current of 40 A, 45 A and 50 A. It was found that with increase in current there is a decrease in the micro hardness value.
- The second set had samples with varying travel speeds of 0.13 m/min, 0.16 m/min and 0.19 m/min respectively. It was found that with increase in travel speed there is an increase in the micro hardness value.
- The difference in hardness value was much smaller / similar at the interface in both cases.
- To evaluate the mechanical properties tensile samples were fabricated using the same technique developed for rapid prototyping small components. Tensile testing was conducted on these samples and the yield stress, ultimate tensile strength and percentage elongation was calculated. These values were compared to AMS 5390 cast standard for the alloy. The values for each of the samples were found to be much higher than the minimum value specified. The exploratory investigations described in this research demonstrate the potential to use welding as a RP technique for component manufacture. The results to date support continuing research in this area.

5.4 FUTURE WORK

This research work can provide the foundation for further work in both areas of blade repair and component build up respectively.

- In blade repair the next step can be to integrate robot based welding with existing pre inspection systems such as 3D scanning and digitizing. Data on amount of wear and therefore the amount of build up can then be used to create the program based on the type of blade.
- Testing in this research has been limited to physical, geometrical and mechanical properties of the weld. Future work can focus on the micro structure of the weld and how the varying weld parameters affect the micro structure of the weld as well as the base material.
- In component build up, the next big step will be the fabrication of several small components. Components can be fabricated to specifications and then subjected to testing or use to determine their usability.
- A simple method of being able to calculate the number of layers and obtaining the 2D data from a 3D model will be a major step in component build up. Integration with the robot will be the key when fabricating components with varying dimensions.
- For both blade repair as well as small component manufacture, future studies can investigate the effect of ‘pulsing’. Pulsing refers to a welding process wherein the current is not steady. “Pulse Width Modulation” techniques wherein the applied current is pulsed, can affect the heat input. The overall heat input may be lower due to the fact that the base current and peak current are not the same and vary between two limits.

VI - REFERENCES

1. Yong-Ak Song, Sehyung Park, Doosun Choi and Haesung Jee,"3D welding and milling: Part I–a direct approach for freeform fabrication of metallic prototypes", International Journal of Machine Tools & Manufacture Vol 45, pp 1057–1062, 2005.

2. R. Kovacevic, "Rapid prototyping technique based on 3d welding", NSF Design & Manufacturing grantees conference, Long beach, California, USA, 1999, website: http://lyle.smu.edu/me/kovacevic/papers/nsf_99_grantees_1.html (Last accessed on 14.October.2010).

3. Todd Grimm, "A user's guide to rapid prototyping", Society of Manufacturing Engineers illustrated edition 2004, ISBN-10: 0872636976.

4. CSA ILLUMINA, "Glossary", Website: www.csa.com/discoveryguides/rapidman/gloss.php (Last accessed on 14.October.2010).

5. Wikipedia, "Rapid prototyping", Website: en.wikipedia.org/wiki/Rapid_prototyping (Last accessed on 14.October.2010).

6. American Welding Society (AWS) Website: www.aws.org, (Last accessed on 14.October.2010).

7. Larry F Jeffus, "Welding: Principles and applications", Delmar Cengage Learning 5th Edition 2002, ISBN-10: 1401810462.

8. Wikipedia, "Arc Welding", Website: en.wikipedia.org/wiki/Arc_welding, (Last accessed on 14.October.2010).

9. Weld Procedures, "Welding terms and definitions" Website: www.weldprocedures.com/weldingterms.html , (Last accessed on 14.October.2010).

10. Jian Gao, Xin Chen, Detao Zheng, Oguzhan Yilmaz and Nabil Gindy, "Adaptive restoration of complex geometry parts through reverse engineering application" Advances in Engineering Software Vol 37, pp 592–600, 2006.

11. Jianming Zheng, Zhongguo Li and Xi Chen, "Worn area modeling for automating the repair of turbine blades", International Journal on Advanced Manufacturing Technology Vol 29, pp 1062–1067, 2006.

12. Bryan tsong-Jye Ng, Wen-Jong-Lin, Xiaoqi Chen, Zhiming Gong and JingBing Zhang "Intelligent system for turbine blade overhaul using robust profile reconstruction algorithm", Control, Automation, Robotics and Vision Conference, ICARCV 2004 , Vol 1, pp 178 – 183, 2004.

13. Bremer C Claus, “Automated repair and overhaul of aero engine and industrial gas turbine components”, Proceedings of ASME Turbo Expo 2005 Vol 2, pp 841 – 846, 2005.

14. Oguzhan Yilmaz, Nabil Gindy and Jian Gao, “A repair and overhaul methodology for aeroengine components”, Robotics and Computer-Integrated Manufacturing Vol 26, pp 190–201, 2010.

15. Jian Gao, Janet Folkes, Oguzhan Yilmaz and Nabil Gindy, “Investigation of a 3D non-contact measurement based blade repair integration system”, Aircraft Engineering and Aerospace Technology: An International Journal Vol 77(1), pp 34–41, 2005.

16. Dr Sun Zheng, Pan Dayou and Dr Kuo Min, “Precision Welding for Edge Buildup and Rapid Prototyping”, SIMTech Technical Report (PT/99/001/JT), Website: http://www.simtech.a-star.edu.sg/Research/TechnicalReports/TR0550.pdf, (Last accessed on 14.October.2010).

17. J. Liburdi, P.Lowden and C.Pilcher, “Integrated weld automation for gas turbine blade repair” American society of mechanical engineers, International gas turbine and aeroengine congress and exposition, Jun 3 – 6 1991.

18. Wan Ling-na, ZhanG Hua, and Hu Rong-hua, “Study of STL data processing on TIG welding rapid manufacture”, Robot : Weld Intelligence & Automation, LNCIS 362, pp 383–389, 2007.

19. XU Jian-ning, ZHANG Hua, ZHANG Guang-yun, LI Yu-long and HU Rong-hua, “The choice of welding parameters and prediction of weld seam dimensions for welding rapid prototyping”, E Conference on Cybernetics and Intelligent Systems, pp 976 – 979, 2008.

20. Huijun Wang, Wenhui Jiang, Jiahu Ouyang and Radovan Kovacevic, “Rapid prototyping of 4043 AL-alloy parts by VP-GTAW”, Journal of Materials Processing Technology 148 pp 93–102, 2004.

21. J. H. Ouyang, H. Wang, and R. Kovacevic, “Rapid prototyping of 5356-aluminum alloy based on variable polarity gas tungsten arc welding: process control and microstructure” Materials and manufacturing processes, Vol 17(1), pp 103–124, 2002.

22. Hussein, N.I.S, “Laser and arc weld methods for direct metal deposition of Waspaloy” International Journal of Manufacturing technology and management, Vol 17(4), pp 419 – 425, 2009.

23. Li Yulong, Zhang Hua, Hu RongHua and Xu Jianning, “Development of a steel rapid prototyping system based on TIG welding deposition technology”, IEEE International

Symposium on Knowledge Acquisition and Modeling Workshop, 2008. KAM Workshop pp 154 – 157, 2008.

24. Fernando Ribeiro and John Norrish, “Making Components with Controlled Metal Deposition”, IEEE International symposium on Industrial electronics, ISIE 97, Guimaraes, Portugal Vol 3, pp 831 – 835, 1997.

25. Toshihide Horii , Soshu Kirihara and Yoshinari Miyamoto, “Freeform fabrication of superalloy objects by 3D micro welding”, Materials and Design Vol 30, pp1093–1097, 2009.

26. PBC Linear, “The Cartesian Robotics System: Simplifying Automation Control” Website: http://www.pbclinear.com/News/The-Cartesian-Robotics-System-Simplifying-Automation-Control, (Last accessed on 14.October.2010).

27. Embedded System Net, “KUKA KR 1000 Titan 6 Axis Industrial Robot, the Guinness Book Strongest Robot”, Website: http://embedded-system.net/kuka-kr-1000-titan-6-axis-industrial-robot-the-guinness-book-strongest-robot.html, (Last accessed on 14.October.2010).

28. T and T Lanco Inc, “The MIG Welding process”, Website: http://www.tandtlanco.com/index_files/page676.htm, (Last accessed on 14.October.2010)

29. Wikipedia, “Gas Tungsten Arc Welding”, Website: http://en.wikipedia.org/wiki/Gas_tungsten_arc_welding, (Last accessed on 14.October.2010).

30. R Scott Funderburk, “Key concepts in welding engineering”, Welding Innovation Vol 16(1), 1999, Website: http://www.jflf.org/pdfs/papers/keyconcepts2.pdf, (Last accessed on 14.October.2010).