# DUAL WELDING OF HIGH STRENGTH LOW ALLOY (HSLA) STEEL AND COMPARISON OF MECHANICAL PROPERTIES WITH INDIVIDUAL WELDING PROCESSES

**By**

**MUHAMMAD IJAZ AFZAL**

**REGISTRATION #**

**2011-NUST-MS-DME-13**

**SUPERVISOR**

**DR SHAHID IKRAM ULLAH BUTT**

**SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING**

**NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY ISLAMABAD**

**DEDICATED**

**TO**

**ALL THOSE WHO LOVE**

**ALLAH**

**AND**

**HIS PROPHET**

**HAZRAT MUHAMMAD (P.B.U.H)**

# Acknowledgments

All praises and humble thanks are to Almighty ALLAH who gave me the valor and strength for successful completion of such a momentous work. No intellectual findings are the result of works of authors only; it includes also the precious contributions of others, which pave the path of success and immortality. Same is true for this MS dissertation work. There are many people who helped and supported me along the way and to whom I feel grateful.

My deep gratitude goes to my MS supervisor Dr. Shahid Ikram Ullah Butt for his initiation and supervision of this study and for his continuous support and engagement in the project. The efforts and supreme guidance of Dr. Shahid Ikram Ullah Butt made it possible for me not only to serve the purpose but also to enhance my research skills as well. I am very grateful for his inspiration and guidance.

The influence of the Guidance and Examination Committee (GEC), comprising of Dr. Liaqat Ali, Dr. Hussein Imran and Dr. Mushtaq Khan is greatly recorded. They inspired in me the taste of research and always encouraged and guided me during the course of current research.

I specially owe my deep gratitude to Dr. M. Ejaz Qureshi for sharing his knowledge, his valuable criticisms, fruitful discussions and continuous guidance and support.

I am also very thankful to Mr.Shahid Nadeem and Mr. Hafeez Imtiaz for their encouragement and technical assistance.

Finally, and most importantly, I would like to express my warmest appreciation to my family and friends. Throughout this process, it has been a comforting feeling to have the support of loved ones that show genuine interest in my work.

**Author**

# Executive Summary

Welding is a major joining technique employed in hi-tech industries like in nuclear, aerospace and aeronautical, submarine and shipbuilding and pressure vessel applications for the production of high performing resilient structures. Tremendous efforts were made in the last couple of decades showing remarkable development in new welding technologies for defect free resilient structures capable of excellent in-service thermal and structural load bearing features.

The objective of this research work is to find the alternative welding methods for welding of aerospace alloys, pressure vessels and in industrial applications. So far, very little attention is given towards multi-process welding (hybrid welding and dual welding). The multi-process welding procedures combine two welding processes for joining of metals on one work-piece. Through multi-process welding, the advantages of two welding processes can be combined. The combination of the two welding processes reduces thermal distortion of the welded work-piece and assures weld penetration. Although some research is done on hybrid welding, but still the dual welding process is mostly unexplored.

Low alloy steels (may or may not requiring post weld strengthening heat treatments depending upon the in-service loadings) along with stainless steels are the potential candidate materials.

Heat Affected Zone (HAZ) and Fusion Zones (FZ) are developed during welding process and subsequent cooling of the metals have significant effect on the microstructures, physical properties, mechanical properties and stress distributions.

In this research work Dual welding process is selected as welding process. Two welding processes are selected and tensile samples are prepared by these welding processes. High Strength Low Alloy (HSLA) steel is used for the welding process. The effects of the dual welding process on the mechanical properties of HSLA steel are studied. The comparison of different mechanical properties such as tensile strength, yield strength, percentage elongation and hardness is made at the end. The microstructure analysis of weld beads has also been made in this work. In the last chapter, the results are discussed and some objectives have also been suggested for further work.

***Key Words:*** *Welding Technology, Hybrid welding, Dual welding, Heat Affected Zone (HAZ), Fusion Zone (FZ).*

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| BC : | Before Christ |
| WS : | Weld speed (mms-1) |
| P : | Density of material (Kgm-3) |
| V : | Voltage (volts) |
| I : | Current (amperes) |
| °C : | Degree Celsius |
| °F : | Degree Fahrenheit |
| Lit/min : | liter per minute |
| Cm/minute: | Centimeter per minute |
| mm : | millimeter |
| Amp: | Ampere |
| MPa : | Mega Pascal |
| PSI : | Pound Square Inch |
| CNC : | Computer Numeric Control |
| ASTM : | American Society for Testing and Materials |
| FZ : | Fusion Zone |
| AC : | Alternating Current |
| DC : | Direct Current |
| DCEN : | Direct Current Electrode Negative |
| DCEP : | Direct Current Electrode Positive |
| DCSP : | Direct Current Straight Polarity |
| DCRP : | Direct Current Reverse Polarity |
| OAW : | Oxyacetylene Welding |
| SMAW : | Shielded Metal Arc Welding |
| GMAW : | Gas Metal Arc Welding |
| GTAW : | Gas Tungsten Arc Welding |
| PAW : | Plasma Arc Welding |
| SAW : | Submerged Arc Welding |
| EBW : | Electron Beam Welding |
| LBW : | Laser Beam Welding |
| HAZ : | Heat Affected Zone |
| MIG : | Metal Inert Gas |
| TIG : | Tungsten Inert Gas |

# TABLE OF CONTENTS

**PAGE NO.**

**PAGE NO.**

**PAGE NO.**

## LIST OF FIGURES AND TABLES

# CHAPTER 01
# INTRODUCTION

## 1.1 INTRODUCTION

Welding technologies are fundamental to engineering and manufacturing. Welding is considered one of the most complex manufacturing processes which involve number of variables and factors contributing towards the final product. Without the ability to make strong and durable joints between materials it would be impossible to produce the many different items we all rely on in our everyday lives. Welding is extensively used in the fabrication of various structures ranging from conventional industrial applications (Buildings, pipelines, trains and bridges, medical implants and electronic devices) to high-tech engineering applications in nuclear, aerospace, marine and high-pressure vessel applications. Welding has reduced the cost of manufacturing and time of manufacturing considerably. Welding offers significant advantages compared to other mechanical joining methods which include flexibility of design, improved structural integrity and weight & cost savings **[1, 2]**. In addition to these merits, the welding process also has some demerits. It also induces thermal strains in the metal regions near the weld, resulting in stresses, which combine to produce internal forces that cause bending, buckling, and rotation. These unwanted bending, buckling and rotations are termed as welding distortions **[3]**. Both weld distortions and residual stresses affect the performance and reliability of the structure under welding **[4]**. Numerous efforts are being made to reduce the unwanted welding distortions. These distortions are the result of the presence of Heat Affected Zone (HAZ) which cannot be avoided, however can be minimized by carefully monitoring and controlling different welding parameters.

The engineers engaged in the manufacturing of welded structures face numerous challenges related to welding day by day. During joining of various structural components, high thermal stresses and distortions are produced. Shop floor engineers have to cope up with these unwanted distortions and have to devise such welding procedures so that these stresses and distortions are minimized and do not affect the performance of structures.

## 1.2 MOTIVATION FOR REASERCH

From the preceding discussion it is evident that welding is the extensively utilized permanent joining method in the fabrication of various structures ranging from conventional industrial applications (Buildings, pipelines, trains and bridges, medical implants and electronic devices) to high-tech engineering applications in nuclear, aerospace, marine and high-pressure vessel applications[1,2]. Welding directly affects the structural integrity and in-service performance of the structure.

Enormous efforts have been made to explore in the past, the different welding processes and their effect on weldment individually at various prestigious academic and research centers around the globe. But so far, very little attention is given towards hybrid welding and dual welding. These welding procedures combine two welding processes for joining of metals. Through these (Hybrid or dual welding) the advantages of two welding processes can be combined. Although some research is done on hybrid welding, but still the dual welding process is mostly unexplored.

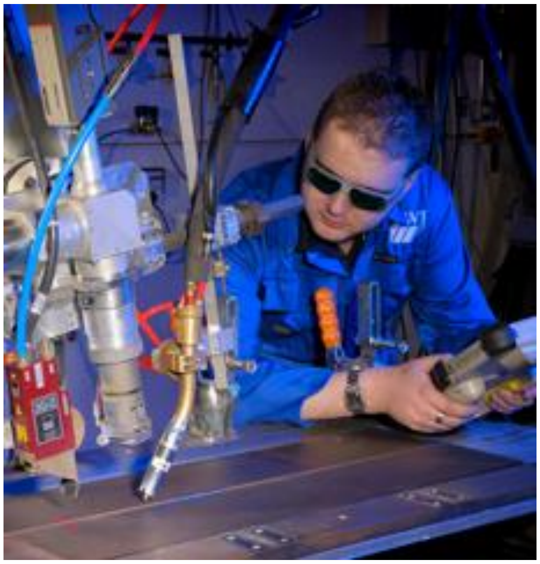


**Fig. 1.1 Hybrid Laser Arc Welding [20]**

Here is an example that shows the advantage of hybrid welding process.

In ship-building, large steel plates that can be up to 30 meters long and 15 millimeters thick are welded together. The gaps between the plates, however, are too large for the laser beam to bridge by itself. To get around this problem, laser welding is combined with MIG welding. The laser delivers the high power densities needed for the deep welds and enables high welding speeds. This, in turn, reduces heat input and distortion. The MIG torch, meanwhile, bridges the gap between the parts and closes the joint using filler wire. On the whole, the hybrid technique is faster than MIG welding alone, and the parts are subject to less distortion **[21]**.

The combination of the two welding processes reduces thermal distortion of the welded work-piece and assures weld penetration.

## 1.3 SCOPE AND OBJECTIVES OF THE RESEARCH

The level of research activities in this dissertation is limited to dual welding (EB+TIG) of High Strength Low Alloy (HSLA) steel and comparison in the variation in mechanical properties after welding with respect to individual welding processes (EB & TIG). HSLA steels are mostly used for aerospace structures because of their high strength and low weight ratio. The HSLA steels have carbon percentage between 0.3 ~ 0.5 % **[23]**. The hardness of HSLA steel can be improved by heat treatment.

The primary aim of this research work is:

**Dual Welding (EB+TIG) Process of High Strength Low Alloy (HSLA) steel and comparison of Mechanical Properties with individual welding processes (EB & TIG).**

Hybrid welding process is the method in which two welding processes act simultaneously (e.g. Laser and TIG) and welding is done with same molten pool to avoid cracks development and distortion **[23]**. In hybrid welding, speed of welding and weld quality is also improved considerably, deep penetrations are achieved. The dual welding process differs little bit from hybrid welding process, as in dual welding two welding processes are not applied simultaneously in the same molten pool.

A dual process is a welding process where two separate weld processes act in a row. First one welding process is being carried out, and then the second welding process is done on already completed welding process.

In this research work, dual welding process will be used. The comparison will be made between the mechanical properties of individual welding processes and dual welding process.

## 1.4 THESIS OUTLINE

The dissertation is organized in six chapters and the significant contribution in each chapter can be conveniently summarized as follows:

Chapter 01 presents introduction to welding process, problems being faced by welding engineers. Based on the effect of welding to the integrity of the structures, motivation for the present research work and in-line with the motivations the scope and objective(s) of the research work are established.

Chapter 02 covers the previous work related research. A comprehensive literature review is made on welding history, different types of welding processes, different welding terminologies, effects of welding on micro-structure of metal. The EBW and TIG Welding processes are discussed in detail and various parameters affecting their performance.

Chapter 03 covers the Design of Experiments conducted using MINITAB software for the optimization of welding parameters. The computers software Minitab s used for this purpose. These optimized parameters are used for welding test coupons.

Chapter 04 covers multi-process welding techniques. This chapter is also some sort of literature review but it is given new chapter number because these welding processes are relatively new and much work is needed to be done in this domain. This chapter covers Hybrid laser welding process and dual welding process.

Chapter 5 is the core of the thesis in the present research work. In this chapter detail of experimental setup employed and experimental validation strategies developed in this dissertation have been presented. It covers detail of research methodology, practical approach adopted, testing and analysis has been discussed.

Chapter 6 covers results and discussions made on research work carried out in chapter 4 and provides valuable recommendations for future work. At the end references have been given.

# CHAPTER 02
# LITERATURE REVIEW

## INTRODUCTION

The welding technology is considered to be started somewhere in 1000 BC. At that time, forge welding process was used in weapons. The Electric fusion welding process was considered to be used first time in Germany in 1782 by G. Lichtenberg **[5]**. However, majority of references point out the start of electric arc welding process in late nineteenth century. A short history of the developments made in welding processes is shown in Figure 2.1 **[6]**.

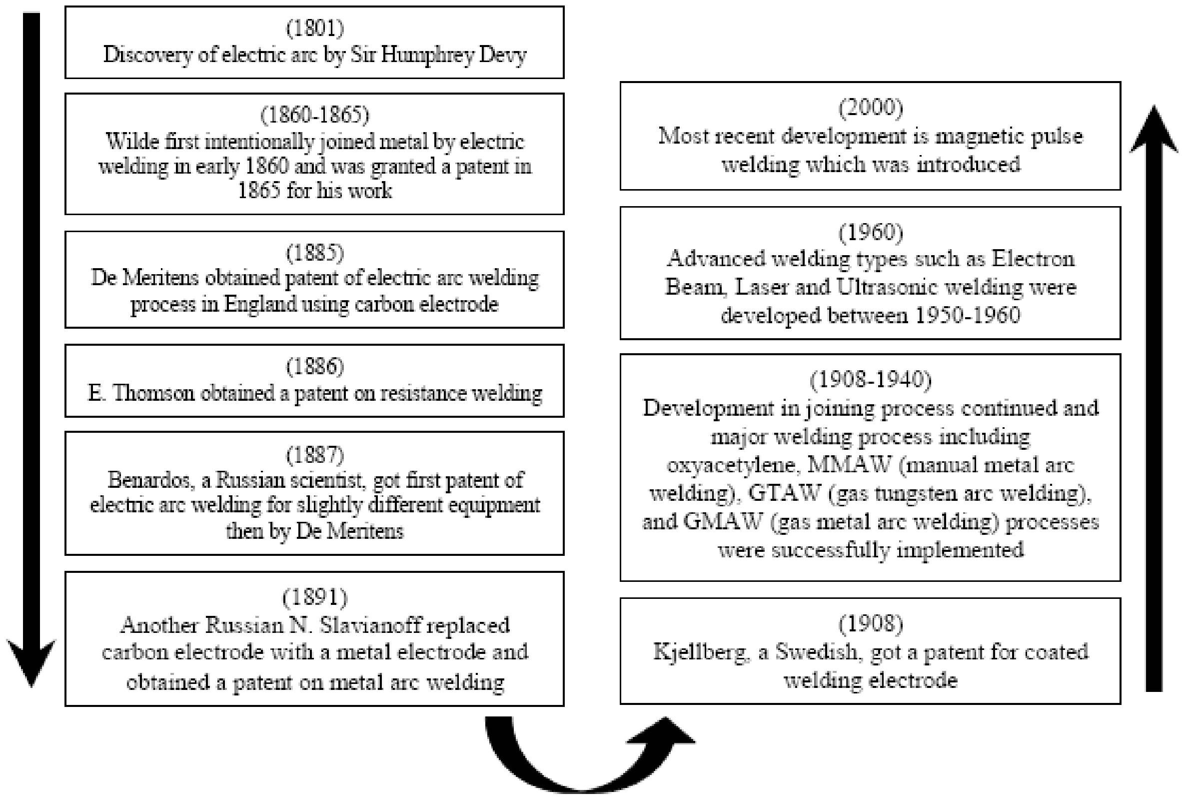



*Figure 2.1 Brief histories of development phases in welding processes*

## 2.1 WELDING TECHNOLOGY

Welding technology is an important part of any mechanical production organization. Welding is the most common metal joining process in the mechanical manufacturing industries. Welding is a joining process used to permanently join materials, usually metals or thermoplastics, together. During welding, the work-pieces to be joined are fused at the joining interface with application of heat and usually a filler material is added to form a weld pool of molten material that solidifies to become a strong permanent joint. Generally, welding can be defined as any process in which two metal pieces are permanently joined together with the application of heat, pressure, or a combination of both.

### 2.1.1 DIFFERENT TYPES OF WELDING PROCESSES

The Welding processes can be divided into two main categories **[7]**:

1. **Pressure Welding**.

   The process in which the metal pieces are welded together by the application of pressure.

2. **Heat Welding**.

   The process in which the metal pieces are welded by applying heat. This is most common welding type in industry.

These two main groups are further subdivided into following main categories.

**1. Gas welding:**

Oxyacetylene welding (OAW)

**2. Arc welding:**

Shielded metal arc welding (SMAW)

Gas–tungsten arc welding (GTAW)

Plasma arc welding (PAW)

Gas–metal arc welding (GMAW)

Flux-cored arc welding (FCAW)

Submerged arc welding (SAW)

**3. High-energy beam welding:**

Electron beam welding (EBW)

Laser beam welding (LBW)

**Figure 2.2 Types of Welding processes**

The brief introduction of all these welding processes is given below.

***Gas Welding***: In this method, combustion of gases produce a focused high temperature flame that melts the pieces to be joined and filler wire together. The Oxy-fuel welding is most wide-spread used type of gas welding in which acetylene and oxygen gases are used for combustion.

***Arc Welding***: An electrical Arc is created and maintained between electrode and work-pieces by a welding power supply. High temperatures are produced in arc welding which melts and fuses the work-pieces to be joined. AC or DC power supply can be used, consumable or non-consumable electrode can be used and a filler wire may or may not be added in arc welding as per requirement.

The most widely used types of Arc Welding processes are:

***Shielded Metal Arc Welding*** **(SMAW):** A coated consumable electrode is used to create the weld in this process. During welding, the electrode and its coating melt and flux is produced as coating disintegrates producing shielding gases. These shielding gases serve two purposes; protect the welding area from atmospheric gases contamination and give molten slag. The filler metal is covered with molten slag as it moves from electrode to the weld pool. Slag is used form the protection of weld contamination during solidification. This slag is removed by chipping to see the finished weld after some time. The process is shown in Fig. 2.3

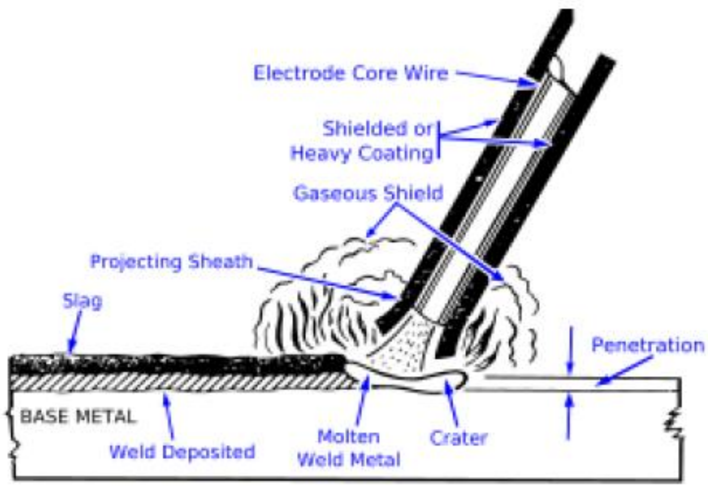



**Fig. 2.3 Schematic of Shielded Metal Arc Welding [23]**

***Gas Metal Arc Welding* (GMAW):** The schematic of GMAW is shown in Figure 2.4. In this process, shielding gas is the mixture of argon and carbon dioxide and are fed to weld area through welding gun. A consumable wire electrode is continuously fed to the weld joint a specified feed rate.

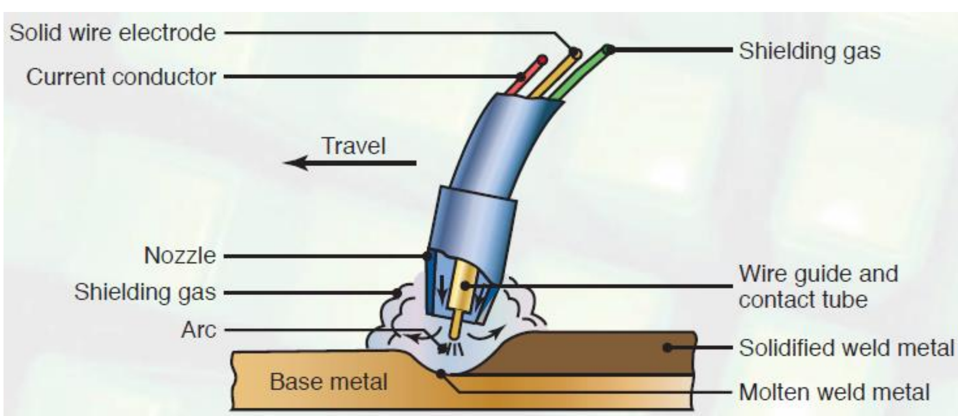



**Fig. 2.4 Schematic of Gas Metal Arc Welding [24]**

***Gas Tungsten Arc Welding*** **(GTAW):** In this process, a non-consumable tungsten electrode is used for the welding. The shielding gas is used for the protection from atmospheric contamination and a filler metal of the same material as the work-pieces is used in this process.

***Energy Beam Welding***: The metal is melted and fused together through a focused high energy beam (Laser beam or electron beam).

***Solid-State Welding***: In Solid State Welding, work-pieces to be joined are not melted in the weld zone instead they are fused in solid state. Some types of this welding are roll welding, ultrasonic welding, friction welding etc.

## 2.1.2 WELDING TERMINOLOGY

Some special terms that are used in welding.

 ***Filler Material***: During welding material is added to fill the gap and space in the work-pieces. This gap or space is filled with filler material. Sometimes filler material is provided from welding rod and sometimes from electrode depending upon the process used.

 ***Welding Rod*****:** Welding rod only supplies filler material to the weld joint. These do not conduct electric current through them.

 ***Electrode*****:** The term electrode comes from the fact that an electric arc is passed, to the metal welded, from this component of welding plant. These are used in arc welding process. They can be divided into two types.

**o** ***Consumable electrodes*** are consumed during the welding process because they provide filler material to the weld joint. They also used as a passage for electric current.

**o** ***Non-consumable electrodes*** are not consumed during the welding process. They do not provide filler material to the weld joint as it is added separately. They are only used as a passage for electric current to produce electric arc for the fusion process

 ***Flux***: The work-pieces to be welded are chemically cleaned before the start of any welding process to remove all impurities such as rust. If the oxides are not properly removed from the material to be welded, weld may contain impurities. The Flux is used to disintegrate oxides and releases trapped gases and slag from the metal during welding. The flux materials are available in many forms and they are selected on the basis of welding type used & work-piece type.

**Root Opening:** Sometimes we leave a space between the work pieces to be welded, in the joint preparation phase. This is called root opening.

**Throat:** The distance between the face center and root of the weld is known as throat of the weld.

**Face:** Outer part of the weld bead which is visible is known as face of the weld.

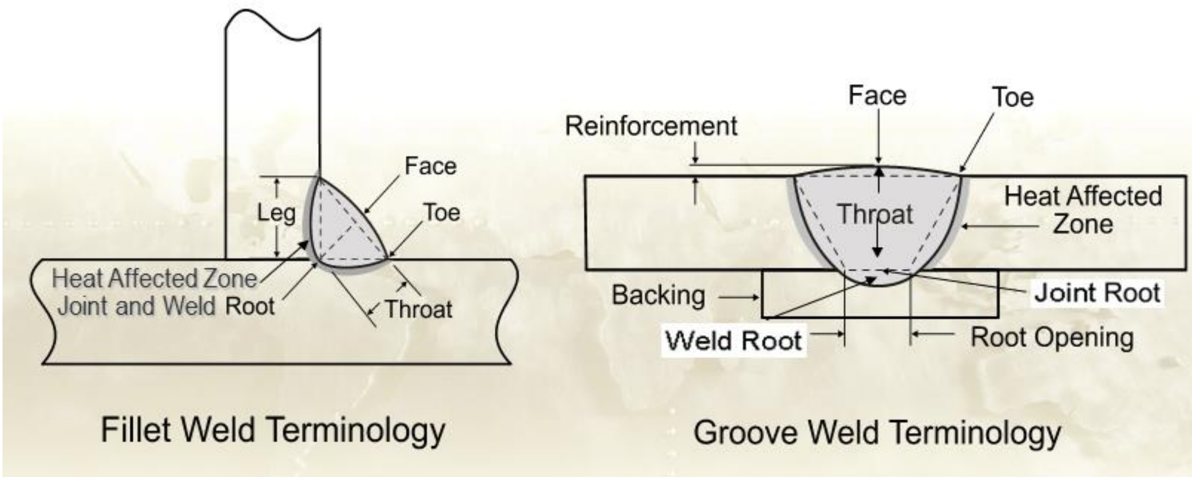



**Fig. 2.5 Different Welding Terminologies [25]**

## 2.1.3 TYPES OF WELD JOINTS

Edges of the work-pieces where welding is done or where fusion is achieved are known as weld joints. Different weld joint types are:

***Butt Joint***: When two pieces of metal, which are under welding, are lined up in the same plane, this is called butt joint.

***Corner and Tee Joints***: T-joints are the joints when T shape is formed by the weld joint. Corner joints are the joints when L shape is formed by the weld joint. Two pieces of metal under welding act at right angle with each other in this case.

***Lap Joint***: One piece rests on the other piece in this type of weld. Welding is done at the edge of one piece and at the face of other piece.

***Edge Joint***: The edges of two pieces of metal under welding lie in the same plane.

These joint types are explained in Fig. 2.5

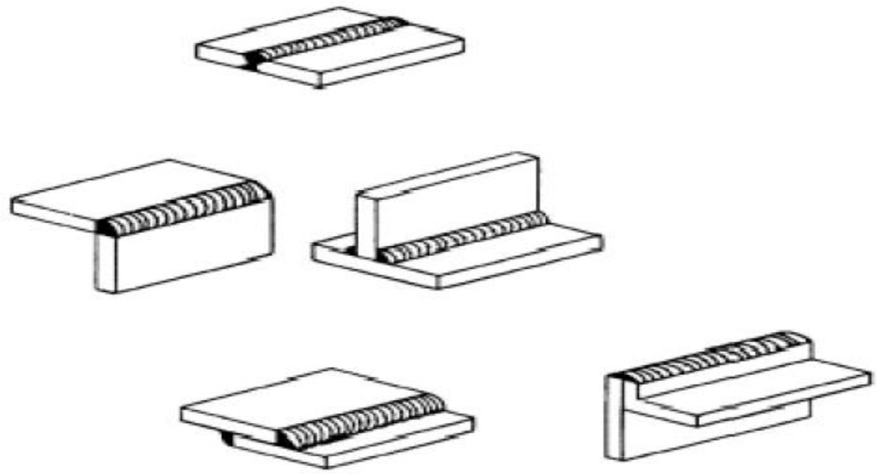


**Fig. 2.6 Different types of Weld Joints [11]**

## 2.1.4 EFFECT OF WELDING ON THE MICRO-STRUCTURE

When the metal work-pieces are welded and fused together, work-pieces melt at the weld zone due to heat input and the grains of base metal melt and re-crystalizes again at and around the weld zone after removal of heat. Immense amount of heat is generated during welding process. The heat generated during welding induces the stresses in the weld joint and welded structures. Due to this melting and re-crystallization of metal, the microstructure of the base metal changes near and at the weld region. The effect of welding process to the base metal microstructure is shown in the Fig. 2.7 & 2.8

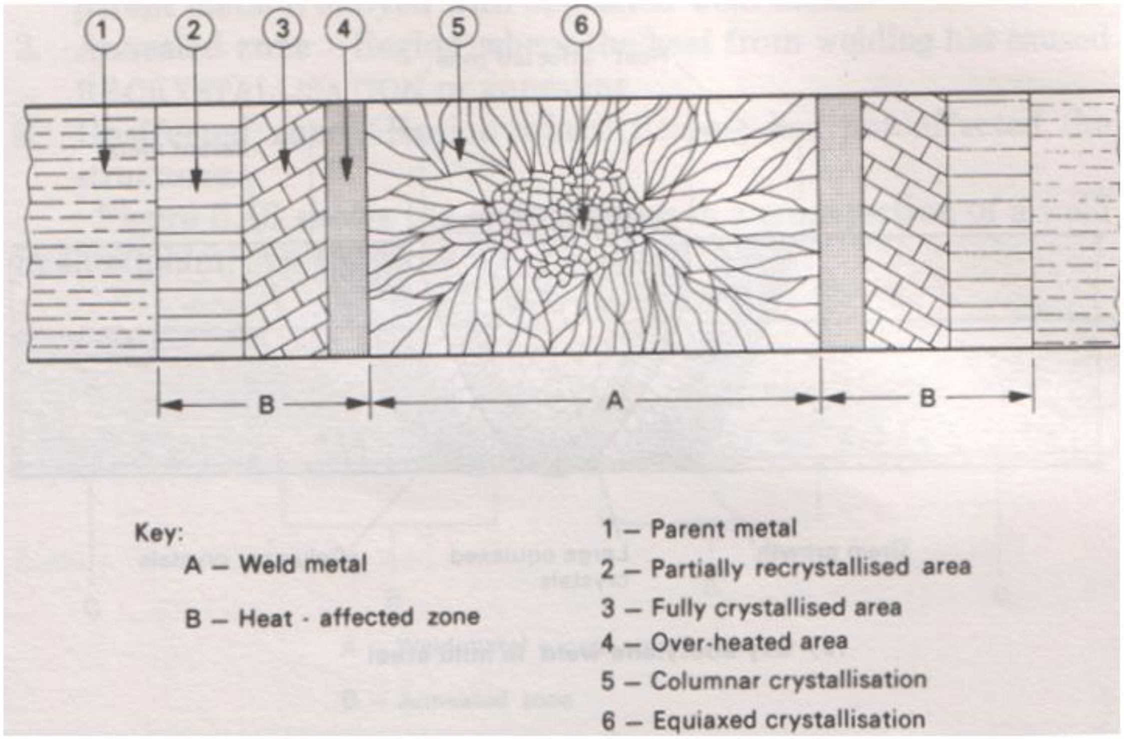



**Fig. 2.7 Effect of welding on the microstructure of base metal**

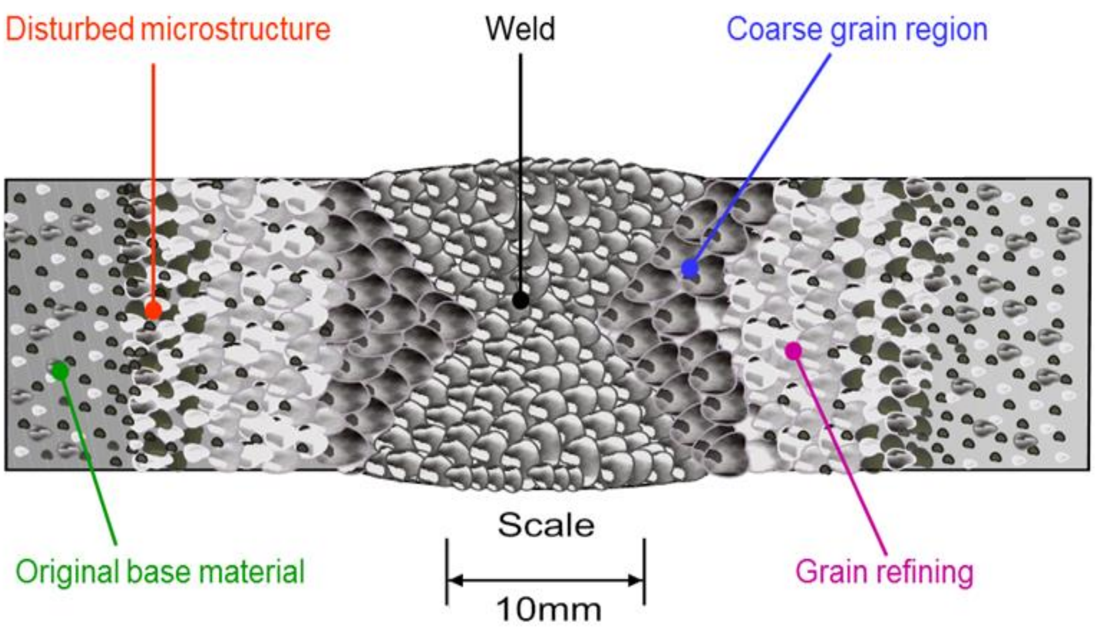



**Fig. 2.8 Effect of welding on the microstructure of base metal**

There are various welding positions on which a welding can be made. Horizontal and vertical positions are considered easiest positions for welding

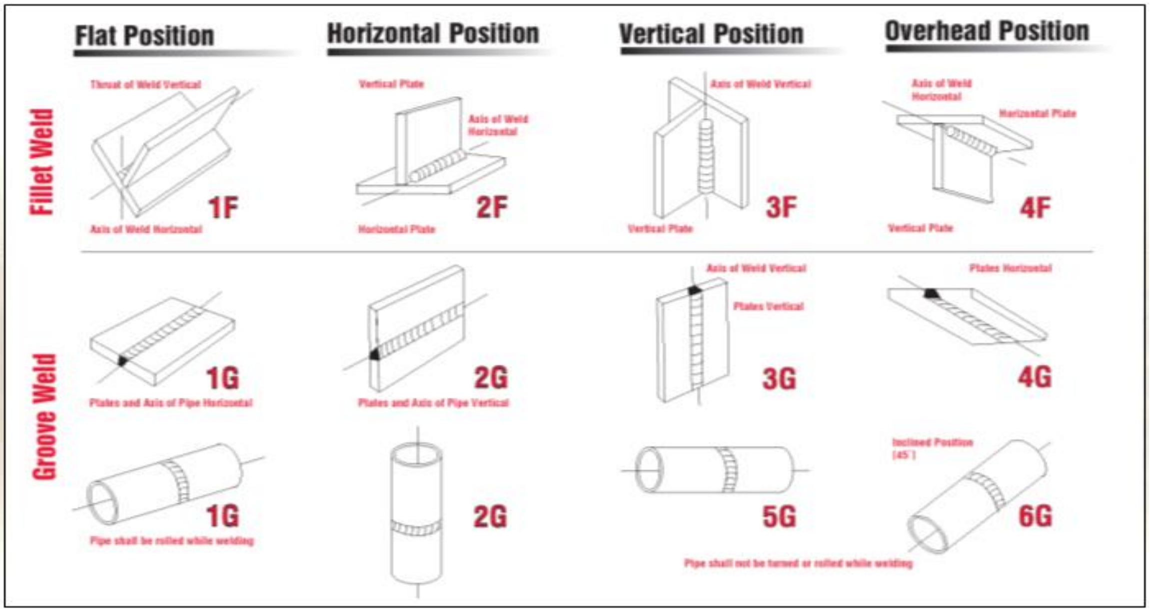



**Fig. 2.9 Positions of welding [25]**

## 2.2 TIG (TUNGSTEN INERT GAS) WELDING PROCESS

TIG Welding, also known as Gas Tungsten Arc Welding (GTAW) is very commonly used type of welding process **[5,6,10]**. The TIG welding process gained popularity during the World War II. This was due to increased demand of fabricated parts for the American aircraft industry. The TIG welding process was used as a method of joining magnesium and aluminum at that time. The magnesium was welded by tungsten electrode and shielding gas used was helium in the late 1930's. TIG welding became an overnight success in the 1940s for joining the metals. TIG welding has important role for the realization of the acceptance of high quality welding and application in the industries. Originally aluminum and stainless steel were welded by this process, whose welding is quite difficult. Now the TIG welding process is used for welding for other alloys as well. TIG welding processes has gained very much popularity and acceptance in the industry very early due to its low cost equipment, availability, excellent quality and versatility of welding equipment and skilled welders. The aerospace, high pressure vessels and aircraft industries are main users of TIG welding process. It has gained very much reputation in industrial applications because the cost of equipment is low and operating cost is also low due to low cost wire. The TIG welding process is shown in Figure 2.10 [10].

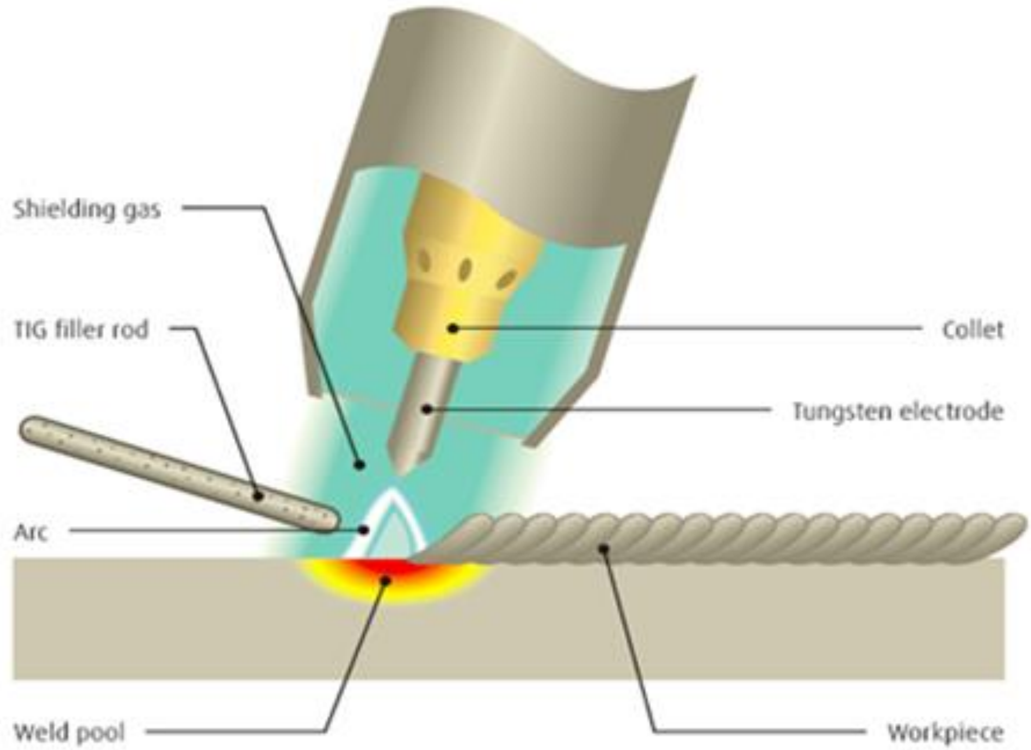



**Fig 2.10 Schematic of the TIG welding process**

TIG welding is a heat type process because heat is passed to the weld join to fuse materials and achieve full penetration. An electric arc is produced and maintained between electrode and the metal and the temperatures of the arc reach up to 2500°C (4530°F) [10]. When electric arc produces this much heat, metal work pieces are melted at the joint and fused with each other causing a good sound weld joint. The electrode used for this welding process is non-consumable tungsten electrode. Argon, helium or a mixture of both argon and helium is used for shielding from atmospheric contaminations. Both are inert gases and make close envelop around the electrode and molten pool. Since welding process does not consume electrode, filler material is added to fill the gaps between the metals under welding for sound quality welds. The welding parameters are determined by experience or from handbook values. Various factors contribute towards quality of weld.

## 2.2.1 VARIABLES IN TIG WELDING

Some basic parameters for good quality welding are explained below:

1. **Material.** Properties of base metal (composition of material, reaction with oxygen, thermal conductivity, coefficient of thermal expansion, and crack sensitivity) are important parameters for welding.

2. **Weld geometry**. Selection of welding process depends upon weld geometry. The joint type (butt, lap, fillet or T-joint) and Bevel type (single-V, double-V or U shape). Weld geometry is an important parameter for producing sound quality weld **[12]**.

3. **Welding Position**. Welding positions also play vital role in weld quality. Mostly the vertical and horizontal welding positions are used for welding. Problems are increased during welding at difficult welding positions because weld quality is affected at difficult positions and more skilled workforce is required to weld at these positions **[12]**.

4. **Shielding Gas (lit/min)**. Shielding gases also play important role in producing good quality welds. These gases are used to keep atmospheric contaminations away during welding phase.

5. **Welding Speed (cm/min)**. Welding speed has very vital role in welding. Penetration and width of weld bead during welding process is dependent on welding speeds. For example, If maximum penetration is accomplished at a given welding speed, if we decrease the weld speed keeping all other parameters same, the weld bead width is increased and vice versa.

6. **Wire Feed Rate (cm/min)**. If we increase the wire feed rate, resistance heating increases and welding current also changes and weld quality is affected.

**7. Material Thickness (mm)**. This parameters plays vital role in penetrations and quality of weld produced and distortions produced during welding. If material selected for welding is thick, heat input for welding will be more and controlling the cooling also becomes critical.

8. **Welding Current (Amp).** It is very important parameter for welding and plays critical role in welding. It is directly proportional to the speed of welding. More the welding current, greater is the welding speed. If we keep the speed fixed and increase the welding current, the penetration will be too high and some material will be melted

through the metals being joined. Similarly if speed is fixed and we decrease the welding current, there will be lack of fusion and less penetration **[11,12,15].**

9. **Welding Voltage (V).** Voltage is as important parameter for welding as is the welding current. It has direct influence on the width of the weld bead and the microstructure of the weld joint. When the voltage is increased while keeping the other parameters fixed, the arc length, the width of the weld bead is also increased and the weld penetration is decreased. When we decrease the voltage, the arc length is decreased and penetration is increased. When we excessively decrease the voltage, arc becomes unstable and crowned bead is produced **[12,15]**.

## 2.2.2 PERFORMANCE MEASURES IN TIG WELDING

Performance measures of welding process are listed, besides toughness, hardness, weld quality, ductility, HAZ etc.:

1. **Weld Strength (MPa)**.

The welding efficiency and production cost is directly affected by this performance measure.

The strength of base metal and weld strength has directly influence on quality of weld. Weld strength depends upon various factors such as the material of the work-pieces, type of welding, type of joint, filler material used, input heat, welding method used etc. A standard tensile test sample is prepared from the test coupon and yield strength and tensile strength are checked to prove that failure will occur in the metal rather than weldment or Heat Affected Zone **[1,6,12,]**.

2. **Weld Induced Residual Stresses (MPa) & Distortions**.

Residual stresses are produced during welding due to heat and distortions are the result of these residual stresses. They affect the performance of the weld quality. Both are not required in the welded joints but they cannot be avoided however they can be minimized with the proper arrangement of welding fixtures, direction of the welding process and other parameter setting such as voltage, current, speed etc. The residual stresses can reach up to the yield stress values and are normally tensile in nature due to the shrinkage of the metal after cooling. The failures of welded parts under low applied stresses occur normally due to these stresses. This type of failure is called pre-mature failure. These stresses are the cause of initiation of cracks and their propagation in the weld. The welded material has less fatigue life if the amount of residual stresses in more in the weld joint. They play an important role for determining fatigue life of metal joints.

3. **Welding Temperatures (**°C).

The temperature produced during welding process by the welding torch is called welding temperature. It is desired to have as low welding temperature as possible to produce a good quality weld and have minimum distortions and stresses due to welding temperature. The value of welding temperature is determined on the basis of thickness of work-pieces under welding, the composition of filler wire and weld parameter settings. High welding temperature produces high Heat Affected Zone.

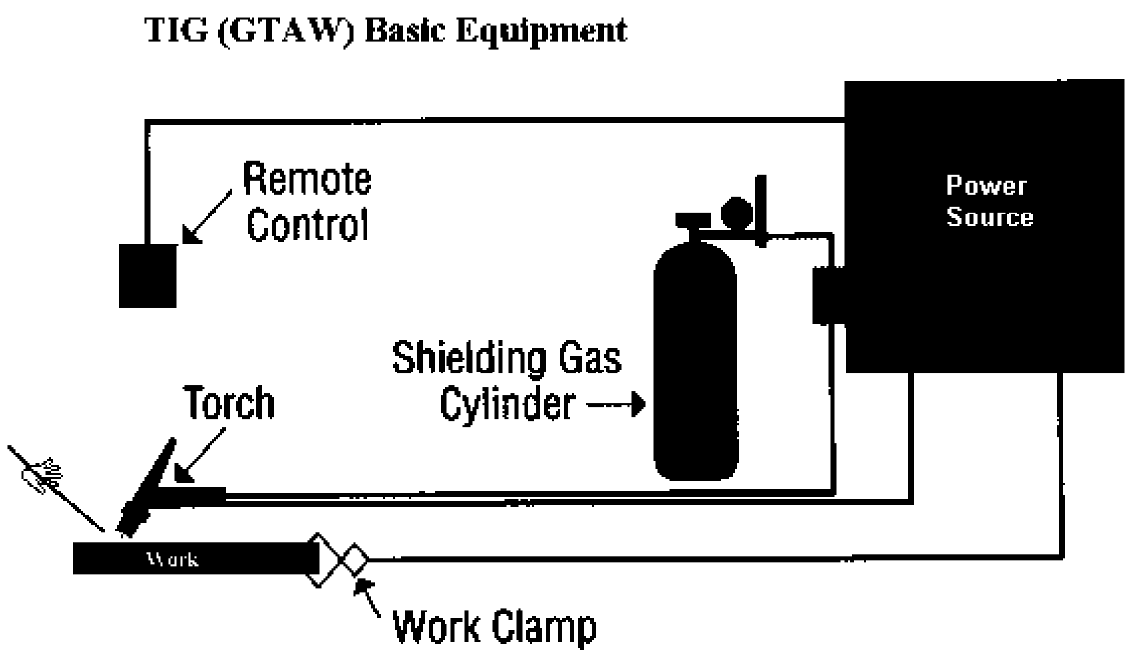
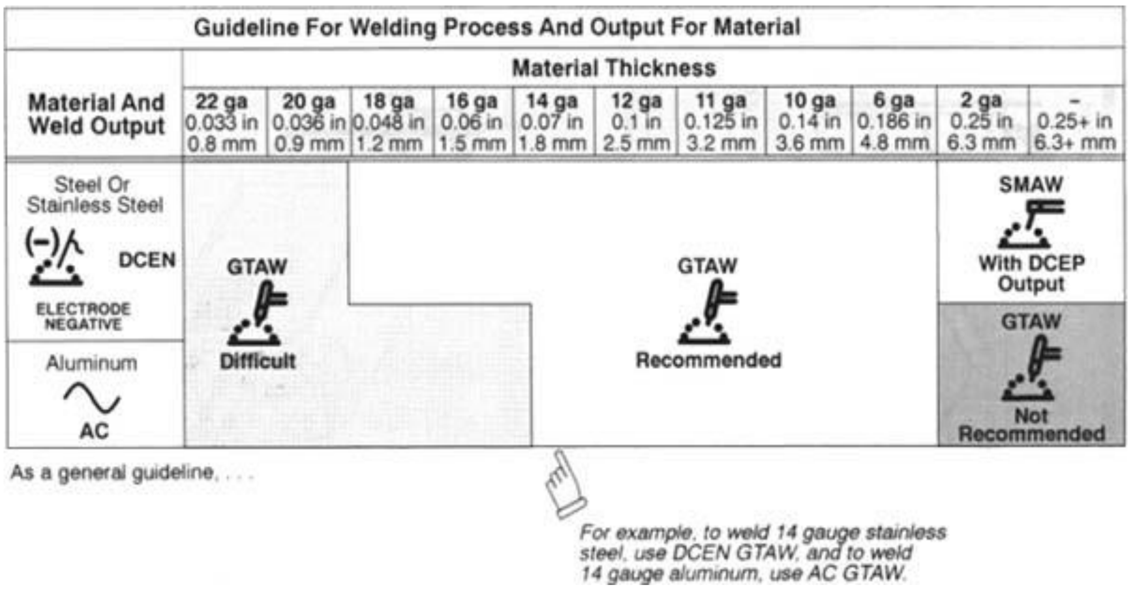



**Fig. 2.11 Basic Equipment of GTAW Process**

Major applications of TIG welding process are Pressure Vessels, fabrication of boilers, aluminum casting, aerospace and aircraft industry.

## 2.2.3 SELECTION OF WELDING PROCESS AND PARAMETERS

Use tables to help select the proper welding process for the type and thickness of metal to be welded. As a general guideline, use AC TIG for welding aluminum/magnesium; use DCEN for all other metals. Use DCEP SMAW (stick) for welding most metal, and use DCEN for some stainless steel application.



Guideline For Welding Process And Output For Material

| Material And Weld Output | Material Thickness | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 22 ga 0.033 in 0.8 mm | 20 ga 0.036 in 0.9 mm | 18 ga 0.048 in 1.2 mm | 16 ga 0.06 in 1.5 mm | 14 ga 0.07 in 1.8 mm | 12 ga 0.1 in 2.5 mm | 11 ga 0.125 in 3.2 mm | 10 ga 0.14 in 3.6 mm | 6 ga 0.186 in 4.8 mm | 2 ga 0.25 in 6.3 mm | - 0.25+ in 6.3+ mm |
| Steel Or Stainless Steel (-) DCEN ELECTRODE NEGATIVE | GTAW Difficult | GTAW Difficult | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | SMAW With DCEP Output | SMAW With DCEP Output |
| Aluminum AC | GTAW Difficult | GTAW Difficult | GTAW Difficult | GTAW Difficult | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Recommended | GTAW Not Recommended | GTAW Not Recommended |

As a general guideline, . . .

*For example, to weld 14 gauge stainless steel, use DCEN GTAW, and to weld 14 gauge aluminum, use AC GTAW.*

**Fig. 2.12.Guidelines for process selection**

**Power Source TIG welding**

The both AC and DC power supply is used in TIG welding plant. The materials to be welded and the welding work-pieces type determine which type of machine is required for welding.

All three types of welding current, or polarities, can be used for TIG welding. Each current has individual featured that it makes more desirable for specific, conditions or with certain types of metals. The major difference among the current is in their heat distribution and the presence or degree of arc cleaning.

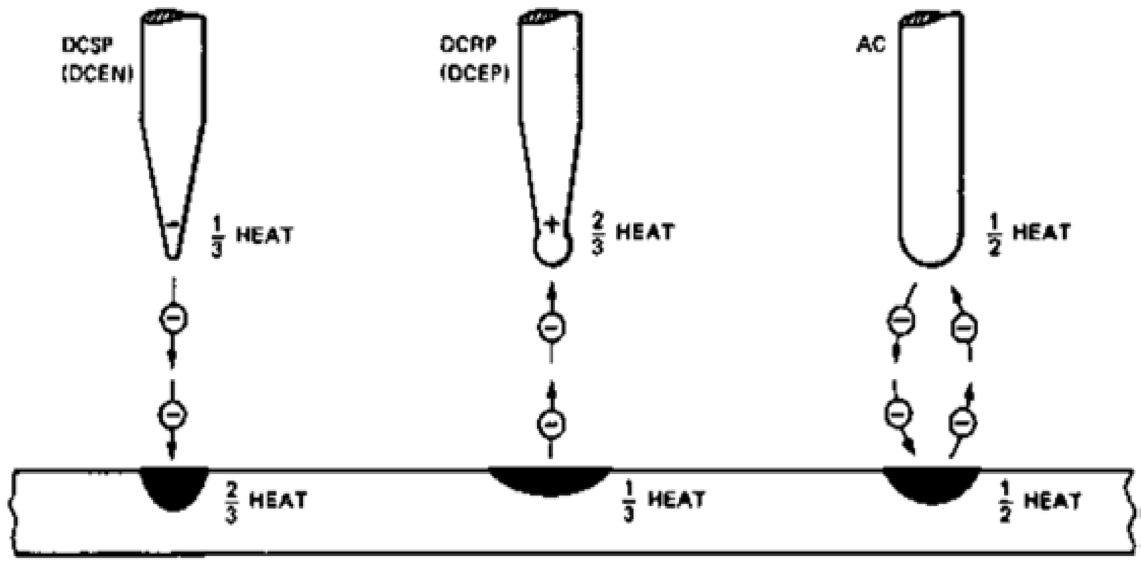



**Fig. 2.13 Heat distribution b/w the tungsten electrode and the work with each type of welding current**

• ***Direct Current electrode negative (DCEN)***, which use to be called direct−current straight polarity (DCSP) current rates about two−thirds of its welding heat on the work and the remaining one−third on the tungsten.

• ***Direct Current electrode positive (DCEP)***, which used to be called direct−current reverse polarity (DCRP), concentrate only one−third of the arc heat on the plate and two−third of the heat on the electrode.

There are many theories as to why DCEP has a cleaning action the most probable explanation that the electrons accelerated from the cathode surface lift the oxides that interfere with their movement. The positive ions accelerated to the metals surface provide additional energy. In combination, the electrons and ions cause the surface erosion needed to produce the cleaning. Although this theory is disputed, it is important to note that DCEP occurs, that it requires argon−rich shield gases and DCEP polarity, and that it can be used to advantage.

• ***Alternating Current (AC)*** concentrates about half of its heat on the work and the other half on the tungsten. Alternating current is DCEN half of the time, DCEP the other half of the time.

**Electric arc:**

The TIG welding process can either use direct current (DC) source or alternating current (AC); the materials to be welded and the welding work-pieces type determine which type of source for welding. With DCEN welding source, deep penetrations and more welding speeds can be achieved. DCEP overheats the electrode due to high temperature at the electrode; weld quality is not good with this source due to electrode burning so this source is strongly not suggested. AC source can be effectively used for aluminum and magnesium to produce super quality welds because it changes polarity continuously and act as cathode cleaning agent and removes oxides from work-pieces. Sine wave, pulsed direct current or square wave AC can also be used as per welding applications

**Electrode:**

Tungsten is used as an electrode in the TIG welding due to its high melting point. The electrode is used as a source of to generate electric arc terminal which provide heat for welding process. The tungsten electrode should not be in contact with molten pool to avoid contamination and faulty welds. The electrode can be improved by adding some other elements such as lanthanum, cerium, thorium and zirconium. This enhances the arc stability and brings higher melting temperatures.

**Fig. 2.14 TIG Welding Process [12]**

**Shielding gases**:

Argon, helium or mixtures of both argon and helium are used as the shielding gases in TIG welding process. Both argon and helium are inert gases. Argon is mostly used in welding due to its excellent arc stability characteristics, low cost and cleaning action in some materials. On the other hand helium gas has high thermal conductivity which is helpful for deeper penetrations but it is costly and lighter gas. Its quantity increases for proper shielding with respect to argon because it is lighter. The two gases characteristics are balanced by using the mixture of both gases.

A comparison of merits and demerits of shielding gases is given in table Fig. 2.15

**Shielding Gas Comparison**

| CHARACTERISTICS | ARGON | ARGON/HELIUM MIXES | HELIUM |
|---|---|---|---|
| Travel Speed | Reduced travel speeds | Improved travel speeds over 100% Argon | Faster travel speeds |
| Penetration | Reduced penetration | Improved penetration over 100% Argon | Increased penetration |
| Cleaning | Good cleaning action | Cleaning properties closer to Argon | Less cleaning action |
| Arc Starting | Easier arc starting | Improved arc starting over 100% Helium | Difficult arc starting |
| Arc Stability | Good arc stability | Improved arc stability over 100% Helium | Less low amperage stability |
| Arc Cone | Focused arc cone | Arc cone shape more focused than w/Helium | Flared arc cone |
| Arc Voltage | Lower arc voltages | Arc voltages between 100% Argon and Helium | Higher arc voltages |
| Flow Rate | Lower flow rates 10-30 CFH | Higher flow rates than Argon | Higher flow rates (2 times) |
| Cost | Lower cost and greater availability | Costs higher than Argon | Higher cost than Argon |

**Fig 2.15 Comparison of properties of shielding gases in TIG Welding [11]**

## 2.2.4 APPLICATIONS OF TIG WELDING

Due to high quality welding at relatively low equipment cost, the TIG welding has become essential tool for most of the manufacturing industries. It has gained much popularity in nuclear and aerospace industries, in industrial applications due to its flexibility and ease of control. It require, however, skilled workforce. TIG welding machines can be semiautomatic, automatic and manual. The TIG welding process can be used to for welding almost all the metals producing good quality welds especially for welding magnesium and aluminum, for reactive metals like zirconium and titanium.

## 2.2.5 MERITS AND DEMERITS OF TIG WELDING

1. The tungsten inert gas process can be used for welding aluminum, magnesium, stainless steel silicon bronze titanium, copper and copper alloy, and wide range of different metal thickness in mild steel **[13]**.
2. Top quality welds made in the above metal need little, if any, cleaning after welding period**[13]**.
3. TIG Welding is most often used for joining aluminum from 1/32 inch to 1/8 inch (0.79 to 3.2 mm) thick. Although heavier sections can be joined by TIG welding, other processes are usually more economical.
4. TIG welding is an easy method of joining metals that are considered hard−to−weld, and filler and base metals can be easily matched. With TIG welding, strip of scrap parent metal may be used for filler metal **[15]**.
5. Post−weld machining, grinding, or chipping can usually be eliminated due to the easily controlled weld reinforcement.
6. The need for flux is eliminated, even on hard to weld metal such as aluminum.
7. TIG welding can weld almost all type of materials.
8. Thin materials are extremely easy to weld by TIG welding.
9. Dissimilar metals can be easily welded by TIG welding

**Disadvantages of TIG welding:**

1. Travel speed is slow as compared to other welding processes.
2. Filler metal deposition rates are low.
3. Skilled workforce is required.

## 2.3 EBW (ELECTRON BEAM WELDING) PROCESS

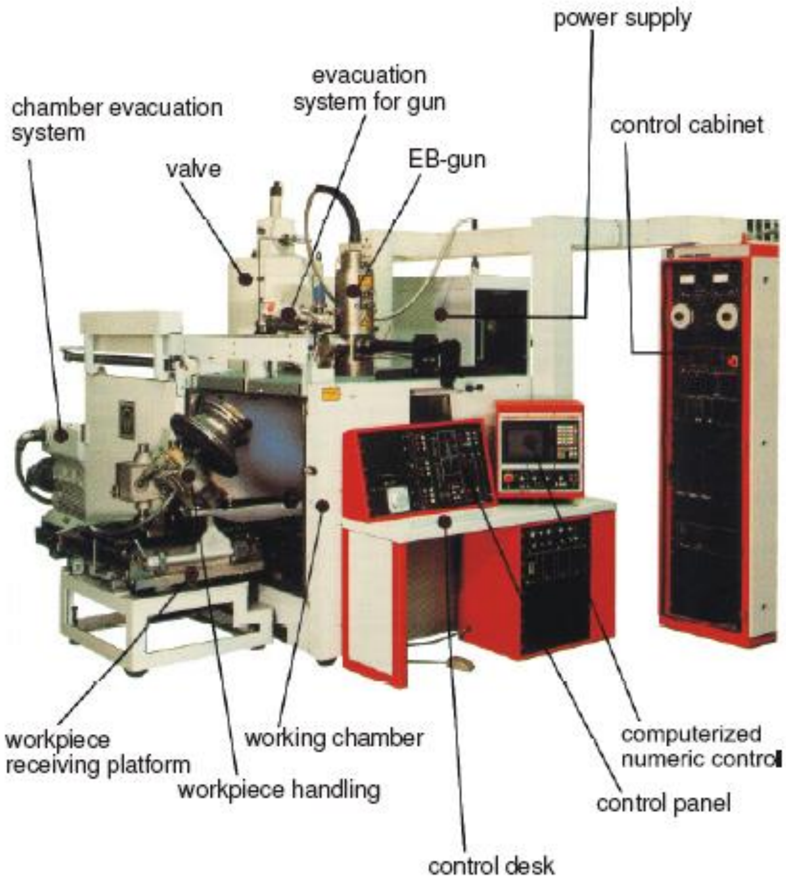



**Fig. 2.16 EBW Machines [17]**

The German physicist Karl-Heinz Steigerwald created the first Electron Beam Welding (EBW) machine. In EBW process, a beam of high-velocity electrons act upon the metals to be welded. The kinetic energy of electrons is converted into heat energy upon collision with the metals to be welded.

The whole welding process is conducted under vacuum. Pressure in vacuum chamber is kept at about $2X10^{-7}$ to $2X10^{-6}$ psi (0.00013 to 0.0013 Pa). This much high vacuum is required otherwise the high velocity electrons will strike at the air molecules before the metal to be joined and will lose their energy on their way to the work-pieces to be welded.

### 2.3.1 WORKING PRINCIPLE OF EBW

The three main parts of EBW machine are:

1. **Beam generation**
2. **Beam manipulation**
3. **Forming and working chamber.** **[18]**

All these three major parts of machine can have one combine vacuum system or they have their separate vacuum systems. The separate vacuum systems offer flexibility as the operator can do his work on each part separately.

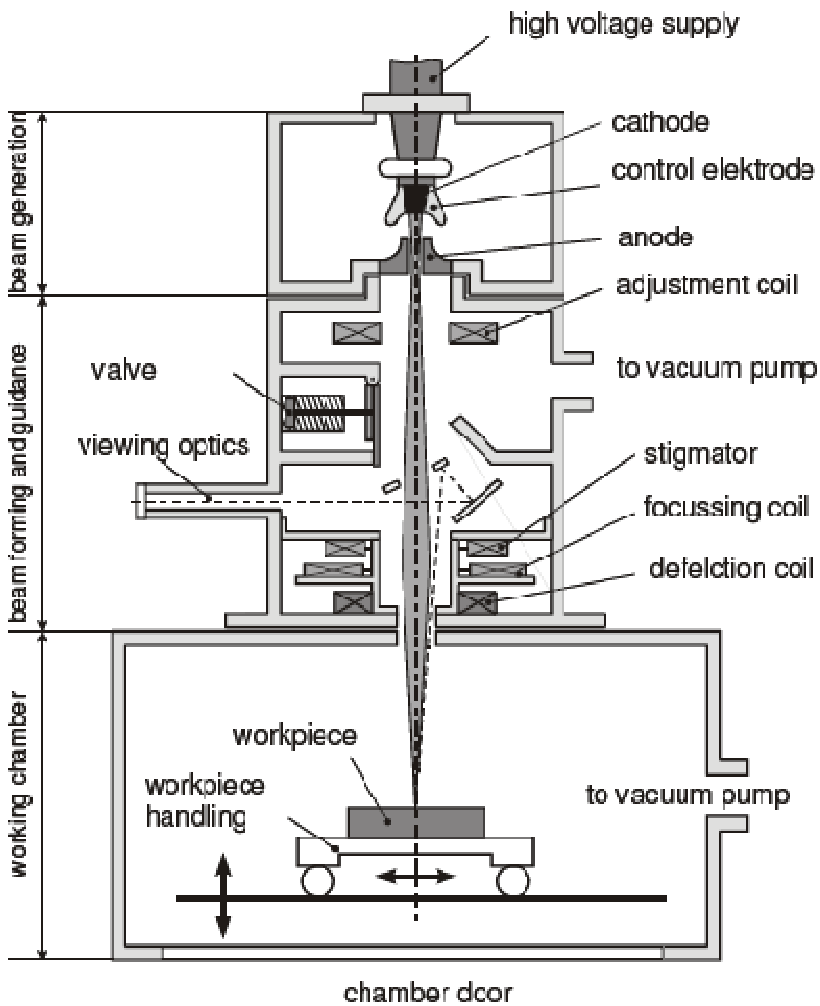
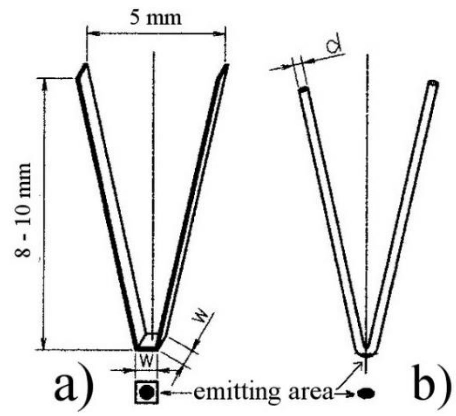
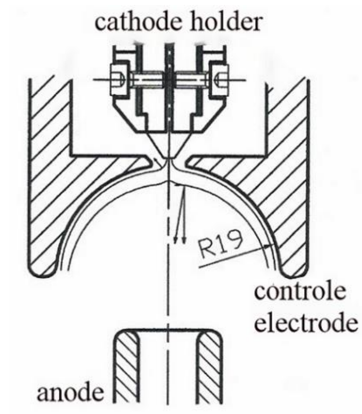



**Fig. 2.17 Working Principle of EBW [16]**

A tungsten cathode is heated up by high current and high voltage under vacuum. This heated cathode releases electron by the process of thermal emission. The direct heating of cathode can be done by filament current or indirect heating can be done by coiled filaments [16,18]. Now these free electrons which were released by thermal emission are accelerated between cathode and pierced anode by the application of high voltage. The tungsten cathode is a sort of strap wire. The tungsten cathode and pierced anode are shown in figure 2.18 [16]. A modulating electrode regulates the electron flow which is positioned between anode and cathode. A barrier filed only passes certain quantity of electrons which is dependent on the cut off voltage and the cathode height[18].

This occurs only when the excess electrons are present in front of cathode in the form of electron cloud.

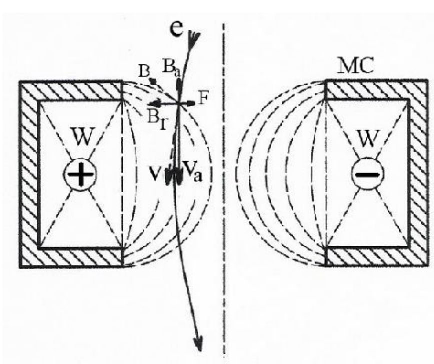



Tungsten Cathode Strap-wire Beam Generator

**Fig. 2.18 Parts of Beam Generation process [18]**

The wehnelt cylinder cathode has a shape similar to concave mirror as is used in light optic. Its function is to focus the beam of electrons electrostatically along with the adjustment of beam current. When the electron beam is passed through the pierced anode, it diverges. The adjustments are made to the electron beam when it passes through the adjustment coil. The electron beam gains the necessary power density for welding process only when it passes through the deflection and focusing coils. The Beam forming and manipulation components are shown in the figure 2.19.





Magnetic Lens Correction and deflection coils

**Fig. 2.19 Components of Beam Forming & Manipulation [18]**

The purpose of electromagnetic focusing lens is to focus the beam on the metal pieces under welding at the weld joint inside the vacuum chamber. Deflection coil is used for keeping the electron beam in oscillating motion. The aberrations of the lenses are corrected with the help of stigmator coil which is also located in the electron beam generator.

An arrangement of lenses is used as a viewing optic system or some video system. This system is used to see the position of the electron beam on the workpiece to be welded in the vacuum chamber. Depending upon the high voltage supply between cathode and anode, the electrons are accelerated at a speed up to 35% - 65% of the speed of light **[17]**.

The major and critical component of the electron beam welding machine is the **electron beam gun[18].** In this component the electron beam is produced under high vacuum. The welding is done in vacuum because as this focused electron beam passes under atmospheric conditions. The electrons will be scattered by the striking at the molecules of air.

Separate vacuum pumps are used to produce vacuum in working chamber and electron beam gun generator. A value is positioned between working chamber and gun generator, known as shut-off valve, to maintain vacuum in the gun generator while the working chamber is open for placing and positioning fixtures and of the work piece. Once all the arrangements are made, the working chamber is closed and air is pumped out of the working chamber.

The electron beam after passing through the gun generator enters into the vacuum chamber and strikes at the workpiece under welding. Viewing optics is arranged in the gun generator so that the beam energy striking at the work piece can be viewed in the video camera. Magnified images of workpiece under welding and beam arrangement can be seen in the camera.

**Beam Interaction in Chamber Cavity:**

The electron beam is targeted at the workpiece under welding in the chamber cavity. The distance between the beam generator and the workpiece is known as shoot distance. This distance is critical, as all the parameters are calculated at this distance and it is the exact replica and representative of the height at which actual part will be welded. This procedure is same for all pre-weld setup requirements. Then the welding operator will follow a process of beam adjustment and beam parameter finalization **[18]**. Once the beam parameters are finalized, the machine is now ready for part welding process.

The electron beam strikes at the marked or aimed location on the part under welding. Energy conversion process takes place as all the kinetic energy of accelerated electrons is converted into thermal energy. Material under welding can either be stationary for straight linear joint (longitudinal) or can be rotated along a desired axis of motion for circular welding (traversed). The motion of the table in the working chamber can be CNC controlled or simple rotary mechanism can be used. The gun generator is stationary and fixed; the welding is carried out on the metal by the motion of the working table in the chamber **[18,19]**.

When the energy of electron beam is converted into heat energy, the metal under welding begins to melt at the joint surface then quick vaporization takes place followed by the resultant coalescence.

### 2.3.2 MODES OF WELDING

Two welding modes are used in the EBW:

**1-Conductance mode:**

This is mode is applicable for thin materials. The weld joint is heated up to melting temperatures quickly at or below the materials surface. This is followed by the thermal conduction throughout the weld joint for full penetration **[27]**. The weld resulted by conductance mode is very small for following reasons:

a- It is created by a concentrated electron beam with high energy density.

b- Because the concentrated beam of electrons is of very high energy, quick travel speeds are possible. The welding occurs at fast speed, minimum heat is absorbed in the base metal close to the weld joint with minimum heat affected zone which is desired.

**2-Keyhole mode:**

This mode is applied when there is requirement of deep penetration in the weld. Since the velocity of electrons is close to the speed of light and high energy is concentrated, deep sub surface penetrations are possible with EBW process. The quick vaporization of the workpiece takes place due to high velocity electrons producing a hole to be drilled in the workpiece material. In this hole cavity, pressure is produced due to quick vaporization and sputtering. This causes suspension of liquidus material against the walls of hole cavity **[26]**. The workpiece moves during welding and hole is also advanced with workpiece movement in the metal. The molten material layer flows around the beam to fill the hole as the workpieces advances and a strong weld joint is formed. The hole and following solidifying metal look like an old fashioned keyhole.

These modes are shown in the Fig 2.20 **[26]** & 2.21 **[27]**. The both modes, conductance and key hole, have same characteristics such as small heat affected zone and small weld joint. The main difference is only that keyhole welding is deep and full penetration welding but conductance welding starts with molten pool and penetration is because of thermal heat conduction.

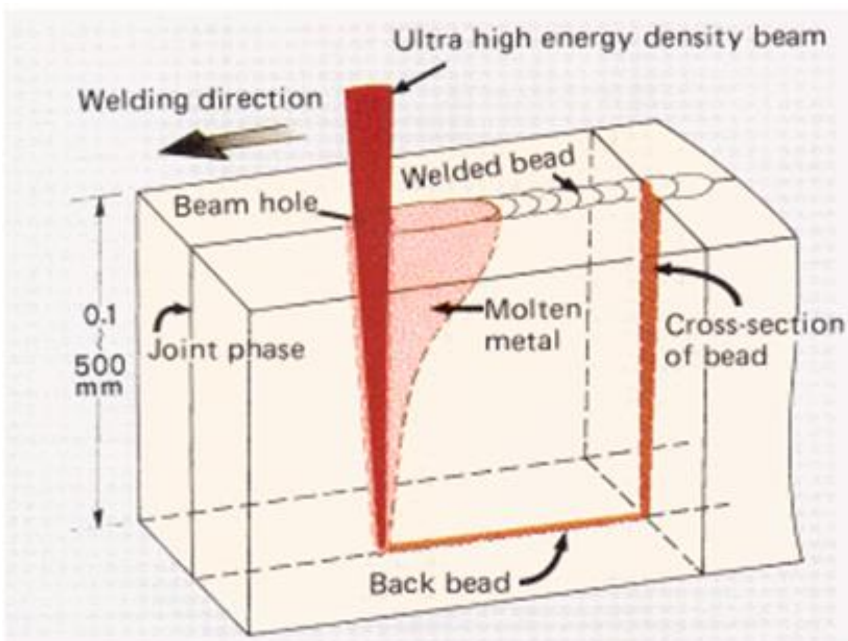



**Fig. 2.20 Keyhole mode**

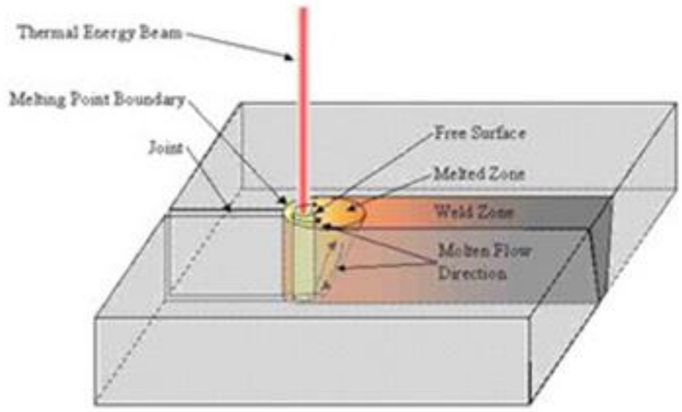



**Fig. 2.21 Conductance mode**

### 2.3.3 PROCESS OF PENETRATION

***Penetration of electrons***

To clarify the ability of election beam welding to create deep and narrow welds, the process of penetration need to be understood. First of all consider how a single electron will interact with the workpiece.

When electron beam strikes at the surface of the metal, some electrons are reflected back called back scattered electrons **[19]**. But majority of electrons penetrate in the surface of the metal and impart all their kinetic energy into the metal particles. Theoretically and experimentally it has been verified that they only penetrate very small distance under the metal surface. The kinetic energy of electron beam is completely converted into heat energy. The distance travelled by the electrons in the metal surface is directly proportional to the initial energy of electrons before striking the metal surface and inversely proportional to the metal density. Normally this distance traveled is of the order of hundreds of a millimeter.

***Penetration of the electron beam.***

The single electron contributes very small heat to the metal under welding. But the high voltage accelerates the electron beam. When the quantity of electrons is increased, known as beam current, the energy of beam can be extended to any desired value. By concentrating the electron beam to a point on the metal surface, high powers up to $10^7$ W/mm$^2$ can be reached. Now as the electrons transfer all their energy to a point at top layer of the metal, the heat at this point reaches to extremely high values and increases extremely rapidly.

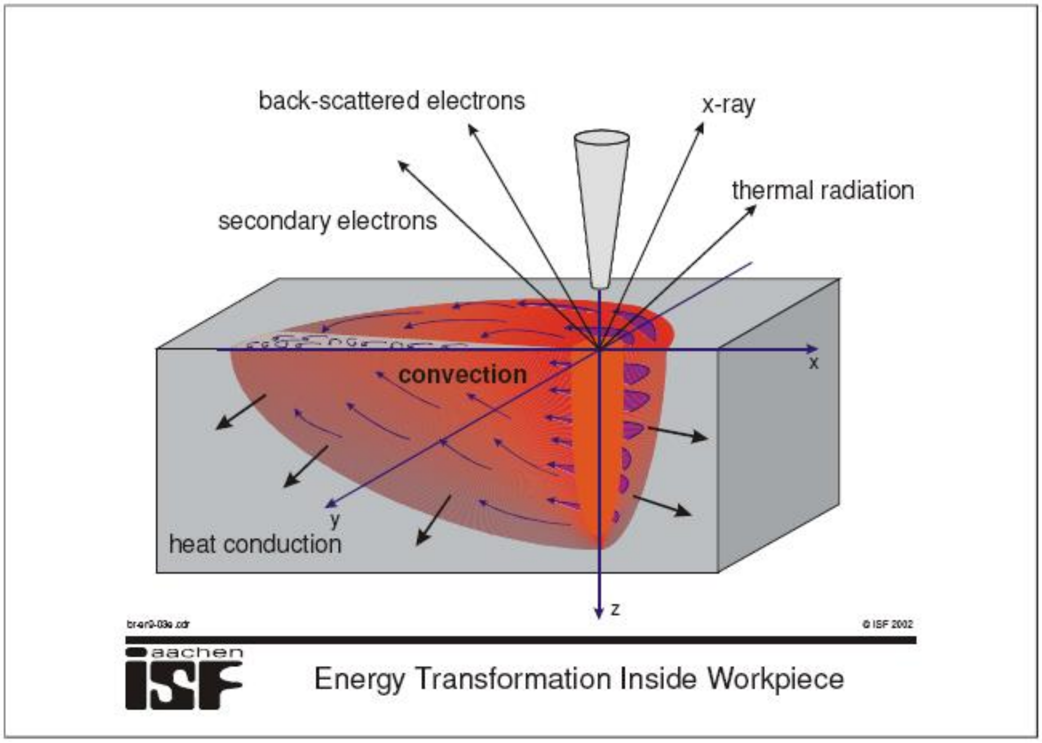



**Fig. 2.22 Energy transformation during EBW Process**

The energy conversion in the work-piece is schematically shown in Figure 2.22. The figure shows that the kinetic energy is not only converted into thermal energy at the point of impact but some energy is also released in the form of radiation and dissipation. A part of the primary electrons are also backscattered. Some x-rays are also omitted from the workpiece.

## 2.3.4 FACTORS AFFECTING THE WELDING PERFORMANCE

The effect of electron beam depends upon following factors;

(1) Beam Power

(2) Power density (focusing of the beam)

(3) Welding speed,

***Beam Power*** – The product of the beam current [mA] and accelerating voltage [kV] is known as Beam Power. This can be easily measured and controlled. At a constant voltage, the power can be controlled by beam current.

***Power Density*** – The power density at the point where electron beam strikes depend upon cathode size, beam alignment, quality of electric and focusing magnetic lenses, accelerating voltage etc. The design of electron beam welding machine determines these factors.

***Welding Speed*** – The speed during welding is determined by the allowable table movement limits in the machine working chamber. The relative motion between beam gun and work piece table is known as welding speed.

These three parameters determine the quality of welding process on EBW machine.

a) Thin surface layer of the metal under welding will only be melted at small power density acting for very short time

b) A defocused beam at low welding speed will not enter into the metal under welding. Metal will be heated by conduction from the surface.

c) At small speed and high power density, deeper penetration and melting zone will be observed. At focused and very high power density, penetration will be proportional to power and deeper penetration will be observed.

## 2.3.5 STEPS FOR QUALITY WELDING ON EBW

Following necessary step must be ensured for obtaining good quality weld on EBW machine

1. **Joint Preparation.**

   Work-pieces to be welded must be prepared for EBW welding. Welding bevel is not required as filler wire is not used in this process. Face of the metal to be welded must be flat and there should be no gap between matting faces to be welded. This is because electrons may pass through the gap affecting the weld quality.

2. **Cleaning of work-piece**

   Work-pieces must be cleaned from contamination and entrapments. As welding process is done under vacuum, these contaminations can produce fumes/gases which will reduce the life of cathode.

3. **Fixturing of work-piece**

   Work-piece should be positioned on the proper clamping fixture because welding is done under vaccum.

4. **De-magnetization of work-piece(if required)**

   Fixtures and parts to be welded on EBW machine must be de-magnetized. This de-magnetization is necessary as the electron beam will be deflected in the vaccum chamber.

5. **Setting up work-piece in chamber**

   As there is not provision to go inside the chamber due to vaccum, so work-piece must be properly set in the chamber.

6. **Pump down air from chamber**

7. **Carry welding process**

   Now the welding operation can be done on the welding machine.

## 2.3.6 MERITS AND DEMERITS OF EBW PROCESS

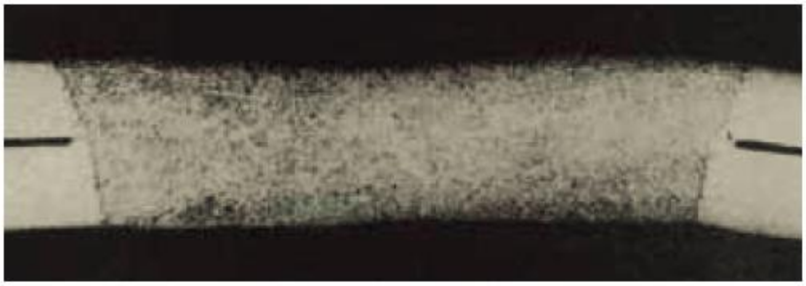
**Advantages**

1. Small Fusion Zone
2. Vacuum welding environment results in highly pure weld joints
3. Heat energy is very low, produced only in the weld zone due to focused electron beam.
4. Many dis-similar metals can be welded on EBW machine and are compatible for welding on this machine.
5. No extra material is added for the welding process.
6. With a proper parameter setup, it is possible to obtain a very smooth and seamless surface finish.
7. Have better welding properties than many other welding processes.
8. Results in faster and cleaner welds.
9. Precise control of heat affected zones is achieved, which is extremely advantageous when welding samples with built-in temperature sensitive components.
10. Distortions are minimum in EB Welded joints.
11. Very small melting zone and heat affected zone.
12. Large thickness parts can be easily welded at high speeds.
13. Welding speed is high
14. No machining is required after welding on the part.

**Limitations**

1. Initial equipment cost is very high
2. Only those pieces can be welded which can fit in the working chamber
3. Takes time to create vacuum in the chamber.
4. In some metals, Speedy solidification can cause cracking.

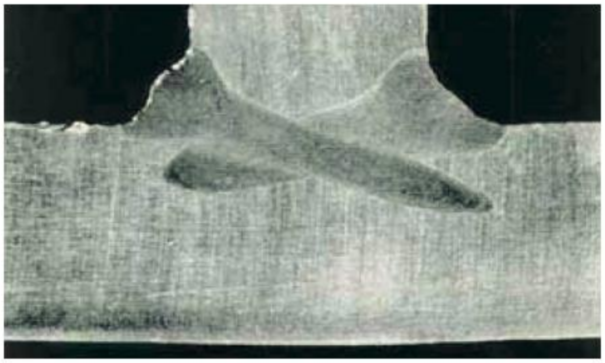
### 2.3.7 EXAMPLES OF EBW WELDING



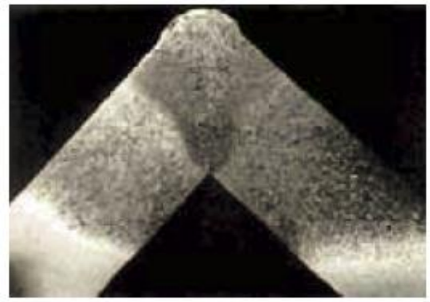
- 2 strips stainless steel of 0.1 mm thickness
- Overlapping welds

- 13% chrome steel
- 20 mm thickness
- One pass penetration butt welding
- Welding speed 1 m/min
- Power 10.3 kW

100 mm thickness titanium butt weld



Fillet welds of stainless steel
Total penetration without deformation



- Zirconium Zr2 of 10 mm thickness
- Fillet weld
- Total penetration 14.2 mm
- Welding speed 1 m/min
- Power 7.2 kW

**Fig. 2.23 Examples of EBW Welding Process [16-19]**

# CHAPTER 03
# OPTIMIZATION OF WELDING PARAMETERS

## 3.1 DESIGN OF EXPERIMENTS

Enough data must be available before planning of every experiment, so that science in any phenomenon can be understood. First trial and error approach is adopted to design experiments.

In this approach, some experiments are performed by trial and error method to get some understanding of the phenomenon. The input variables of every experiment are noted and response to those variables is also noted. Sometimes these experiments do not give positive result and we have to conduct other experiments by changing some input variables. Therefore a number of experiments are performed to reach to conclusion and to understand the problem phenomenon in a better way.

Design of experiments is a well-planned and much better approach than the trial and error approach to obtain good prediction about the input parameters. First of all, the factors which are important for explaining the process variation are sorted out by brainstorming and previous experience. Then understanding is developed how these factors will interact in the process to find out the optimal process performance.

## 3.2 INPUT/PREDICTOR VARIABLES

These are the variables whose effect on response/performance measure are tested in the experimentation. These variable are actually process input variables/parameters or control factors. These inputs are converted into output/response by means of process.

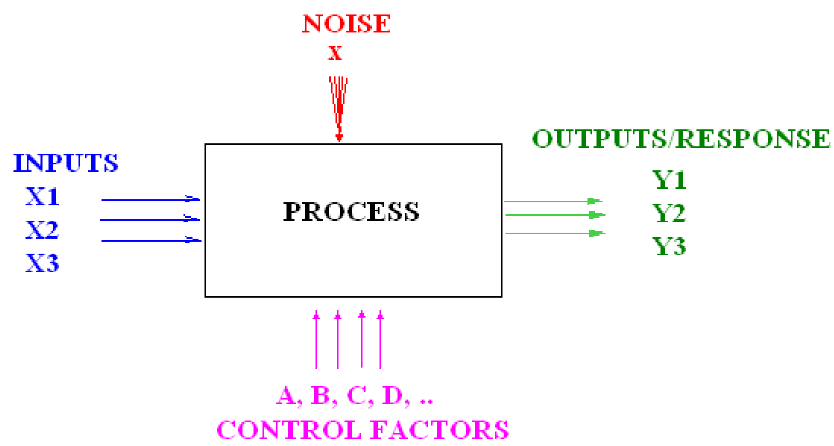



**Fig. 3.1** Process for design of experiments

By brainstorming, the important factors that could possibly affect the output of TIG welding are listed.

1. Welding Current (Amp) (170-285)
2. Welding Voltage (Volts) (10-15)
3. Welding Speed (cm/min) (15-20)
4. Gas Flow Rate (L/min) (20-25)
5. Trailing Flow Rate (L/min) (20-25)

The initial settings of these variables are shown in table 3.1

**Table 3.1 Initial settings of Predictor Variables**

| Test No. | Welding Current (Amp) | Welding Voltage (V) | Welding Speed (cm/min) | wire speed (cm/min | Shielding Gas (l/min) |
|---|---|---|---|---|---|
| 1 | 17 | 10 | 15 | 110 | 20 |
| 2 | 170 | 15 | 20 | 130 | 25 |
| 3 | 285 | 10 | 15 | 110 | 20 |
| 4 | 285 | 15 | 20 | 130 | 25 |

With high and low values of these variables, 04 experiments were performed to analyze the output response as shown in the table above. In these experiments, the weld bead is the response variable for good quality weld. For test no 03, welding penetration was very good while the test no 04 produced only satisfactory quality weld. The test no 01 & 02 showed poor weld quality and result was not satisfactory. Even there was no penetration in due to low values of current, voltage and other parameters. Quality determining parameters of weld bead are shown in figure 3.2 and these are graphed by giving rank value from 1 to 5, low to high, value. The visual inspection method was applied to check the quality of weld bead.

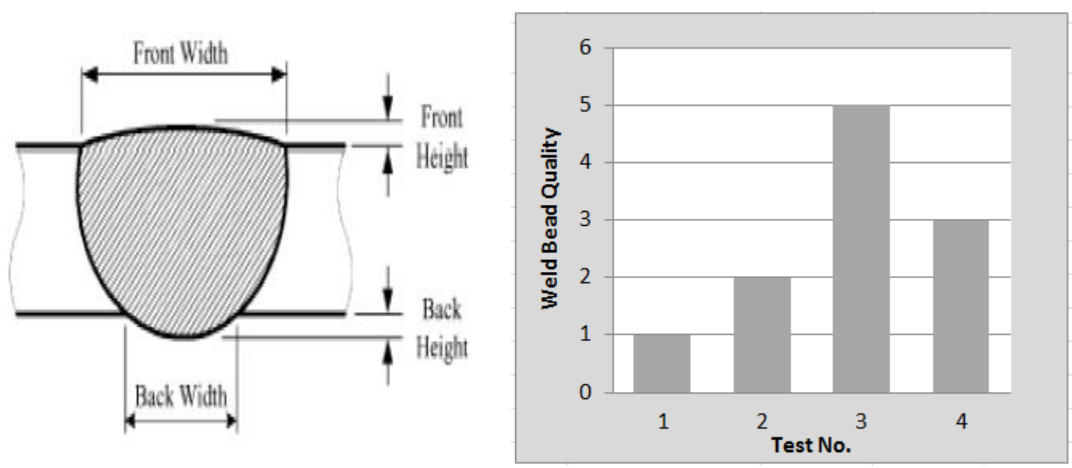



**Fig. 3.2** Initial setting of predictors and Weld quality

The current is very important parameter. It has high values as compared to voltage, speed and wire speed. The review of these parameters and there levels is required. These initial parameters were revised and their new low and high values are required for experimentation work.

## 3.3 FACTORIAL DESIGN OF EXPERIMENTS

The effect of several factors on a process can be studied simultaneously by factorial design of experiments. Varying different factor levels simultaneously rather than one factor at a time, saves considerable time and resources in terms of cost, and at the same time interaction between different factors can be studies. The screening is done to reduce the input variables that affect the quality of product and to focus only on few important variables. Two level full and fractional factorial design of experiment approach is used for screening the important variables/factors that affect the process response measures.
The useful information is gathered at relatively small runs per input variable and indication is given about the main tendencies to guide for further experiments and optimum settings.

Now for the optimal welding parameters, a full factorial model is used in which 4 factors and input variables, two levels of each factor are included and in this way it becomes 16 experimentation parameters. The high and low settings of these four input variables are shown in table 3.2. The Minitab software package and Design Expert package are used for Design of Experiments and all these values are put in the model. The model designed 16 experiments with different input variables combinations as shown in Table 3.3

**Table 3.2 High and Low Settings of Factors**

| Factor | Name | Units | Type | Low Actual | High Actual |
|---|---|---|---|---|---|
| A | Current | W | Numeric | 1800 | 2100 |
| B | Voltage | mA | Numeric | 380 | 410 |
| C | Weld Speed | cm/min | Numeric | 570.00 | 630.00 |
| D | Shielding gas | l/min | Categoric | nil | Ar mixt. |

**Table 3.3** Design of 16 Experiments following Full Factorial

| Std | Run | Factor 1 A:Current A | Factor 2 B:Voltage V | Factor 3 C:Weld Speed cm/min | Factor 4 D: Shielding Gas Yes/No |
|---|---|---|---|---|---|
| 12 | 1 | 270.00 | 13.50 | 15.00 | Ar mixt. |
| 5 | 2 | 230.00 | 10.50 | 18.00 | nil |
| 1 | 3 | 230.00 | 10.50 | 15.00 | nil |
| 3 | 4 | 230.00 | 13.50 | 15.00 | nil |
| 11 | 5 | 230.00 | 13.50 | 15.00 | Ar mixt. |
| 7 | 6 | 230.00 | 13.50 | 18.00 | nil |
| 8 | 7 | 270.00 | 13.50 | 18.00 | nil |
| 16 | 8 | 270.00 | 13.50 | 18.00 | Ar mixt. |
| 13 | 9 | 230.00 | 10.50 | 18.00 | Ar mixt. |
| 4 | 10 | 270.00 | 13.50 | 15.00 | nil |
| 9 | 11 | 230.00 | 10.50 | 15.00 | Ar mixt. |
| 10 | 12 | 270.00 | 10.50 | 15.00 | Ar mixt. |
| 2 | 13 | 270.00 | 10.50 | 15.00 | nil |
| 6 | 14 | 270.00 | 10.50 | 18.00 | nil |
| 15 | 15 | 230.00 | 13.50 | 18.00 | Ar mixt. |
| 14 | 16 | 270.00 | 10.50 | 18.00 | Ar mixt. |

## 3.4 RESPONSE VARIABLE

The output variables or parameters from the process are termed as Response variable. Following response variable is critical and need to be checked in order to see the performance of the HSLA steel tensile test sample welded on the above quoted input variables.

**Weld Strength:** Max tensile strength to be measured on the tensile sample (MPa)

## 3.5 FIXED PARAMETERS

The Flat Horizontal welding position was used in this experiment and geometry of joint was single V with included angle of 70 degree with 1mm root gap and 1mm root face. The DCSP current was used. Mixture of argon and helium shielding and trailing gases (25 l/min) was used.

## 3.6 EXPERIMENTAL RESULTS, ANOVA

The effects of predictor variables upon the response are discussed with respect to analysis of variance (ANOVA), regression and optimization applied to test results of tensile samples.

The relationship between input variables and response/output is investigated and modeled using the analysis of variance (ANOVA). This was developed by Ronald Fisher to interpret the results of agricultural experimentation. The welding process parameters which can affect the response of the system are checked and investigated with ANOVA.

The importance of the welding process parameter is evaluated by percentage contribution in the total sum of the squared deviations.

The significance of the effect of welding process parameter is determined by the F-test, named after Fisher. When F-test value is more than 4, then the process input parameters are significant and play important role in the output response.

ANOVA determines the model with respect to following important values:

- Model F Value & associated probability values to test model significance.
- Forecasted/Predicted R-Squared and R-Squared after adjustment (Adjusted R-Squared) are reasonably in agreement.
- Appropriate Accuracy/Precision (signal to noise ratio) to use model to navigate design space.
- Testing to confirm on individual terms that they are meaningful/significant.

The relationship between input predictors and response variable/output is modeled and investigated by regression analysis. The regression methods which are used to interpret parameters are: the least squares, partial least squares and logistic variables.

Responses/outputs can be optimized by using the point prediction node both numerically and graphically. Desirability is the function that ranges from 0 outside of the limits to 1 at the goal. The maximization of this objective function (desirability) is found through numerical optimization

### 3.6.1 WELD STRENGTH

The comparison of weld strength is shown in the Figure 3.3 for 16 experiments designed above.

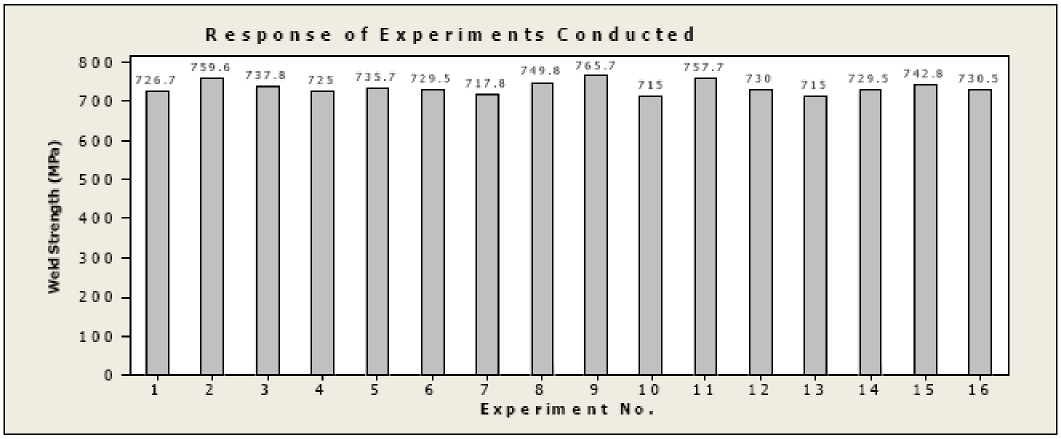



**Fig. 3.3** Weld Strength after tensile testing

**Table 3.4** Max. and Min. Values of Weld Strength Response

| Response | Units | Minimum | Maximum | Mean | Std. Dev. |
|---|---|---|---|---|---|
| Tensile Strength | MPa | 715 | 765.7 | 735.506 | 15.7428 |

The ANOVA is used to analyze the tensile strength and it predicted the observations which are listed in Table 3.5. The analysis shows that input parameters have significant effect on the output response.

**Table 3.5** ANOVA for Tensile Strength factorial model

| Source | Sum sqrs | DoF | Mean square | F-value | Prob>F | Significance |
|---|---|---|---|---|---|---|
| Model | 2827.49 | 4 | 706.87 | 8.74 | 0.0020 | Significant |
| A-Current | 1216.27 | 1 | 1216.27 | 15.03 | 0.0026 | Significant |
| B-Voltage | 435.77 | 1 | 435.77 | 5.39 | 0.0405 | Significant |
| C-Weld Speed | 423.33 | 1 | 423.33 | 5.23 | 0.0430 | Significant |
| D- Trailing | 752.13 | 1 | 752.13 | 9.30 | 0.0111 | Significant |
| Residual | 890.04 | 11 | 80.91 | | | |
| Cor Total | 3717.53 | 15 | | | | |

The F Value of Model (8.74) indicates that it is significant model. The probability that the F Value is due to noise is only 0.20%. The all the model input variables (terms) are significant.

In the table 3.5, the current, voltage, speed and trailing all are model terms. This model is worthy to navigate the design space.

The graphs are shown in the figure 3.4 and these graphs represent the effects of altering the levels of each setting/parameter on strength of the weld while three other parameters are fixed. The strength of the weld decreases with increase of welding current because the heat input increases. The strength of the weld decreases with increase of voltage because this also increases the heat-input. However the strength of the weld increases with increase of speed of welding.

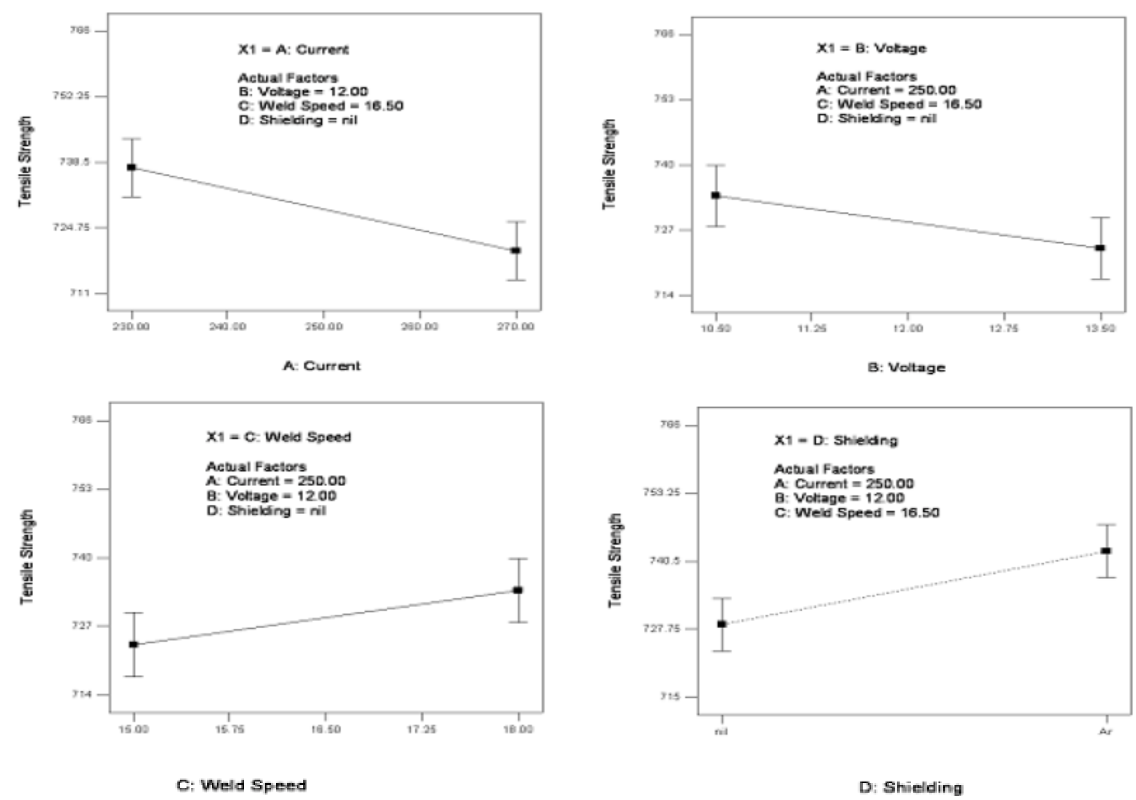



**Fig. 3.4** Effects of welding parameters upon Tensile Strength

The weld strength data is put in the software and the numerical optimization is applied. The optimization indicates that in TIG welding of high strength low alloy steel can be maximized with the following conditions: the low values of current, low values of voltage, high values of speed of welding along with the trailing gas. The optimization plot shows the predicted weld strength (762 MPa) at the optimum input variables/parameters 230.00 Ampere current, 10.5 Volt Voltage and 18cm/min speed of welding as can be seen in the figure 3.5

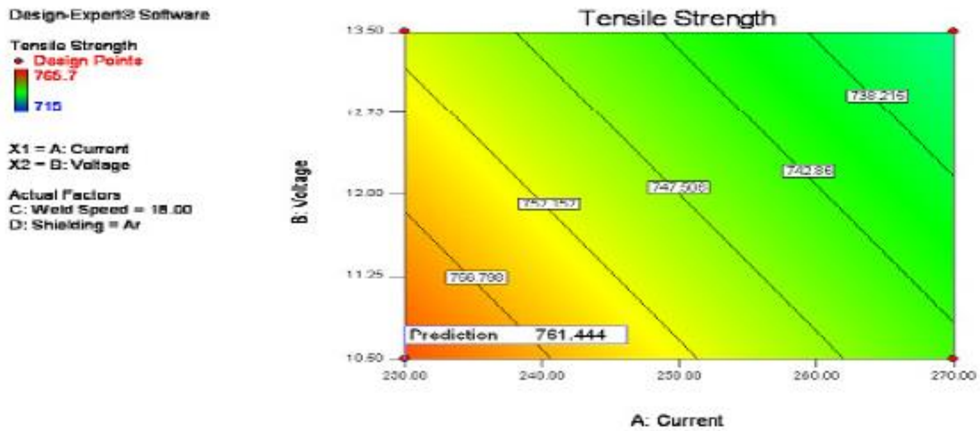



**Fig. 3.5** optimization plot of tensile strength

# CHAPTER 04
# MULTI-PROCESS WELDING

## INTRODUCTION

Welding is considered one of the most complex manufacturing processes which involve number of variables and factors contributing towards the final product. The new advancement in welding technology is that multiple welding processes can be combined together to achieve the benefits of both welding processes. Some industries have successfully applied the laser beam welding process with TIG welding Process.

The multi process welding can be classified in two types

- Dual Welding Process
- Laser Hybrid Welding Process

## 4.1 DUAL WELDING PROCESS

A dual process is a welding process where two separate weld processes act in a row. First one welding process is being carried out, and then the second welding process is done on already completed welding process.

In this type of welding, main goal is to reduce the Heat Affected Zone (HAZ) and get the deep penetrations without having much effect on the properties of work-pieces **[20]**. It is considered that the strength of the dual welded weld-joint can be in between the two individual welding processes for the same type of work-pieces. Special applications can be achieved for aerospace, high pressure vessels, aircraft industry.

## 4.2 LASER HYBRID WELDING PROCESS

Some special steel applications can be achieved, when we combine laser welding process and any other welding process.

Hybrid welding process can be defined as, the combination of laser welding with any other welding process. From this definition we can say that, when laser welding and arc welding work together simultaneously in one welding zone affecting and supporting each other, it is called hybrid laser-arc welding process **[21]**.

We can combine laser welding with other compatible welding processes. Welding processes which are compatible with laser welding are MIG (metal inert gas) or MAG (metal active gas) welding as well as TIG (tungsten inert gas) or plasma welding **[22]**.

Hybrid welding process is the method in which two welding processes act simultaneously and welding is done with same molten pool **[23]**. Two systems will affect each other in different ways, depending on the kind of laser or arc process utilized and also on the process parameters.

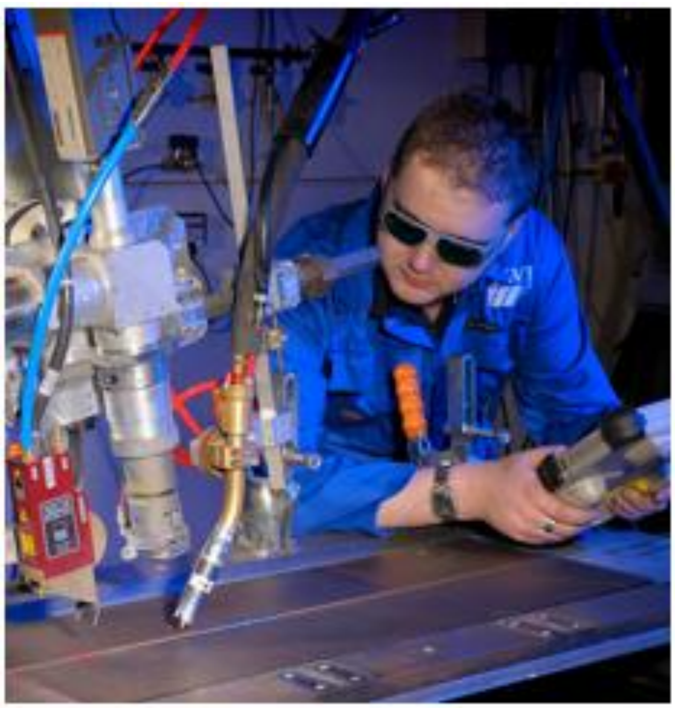
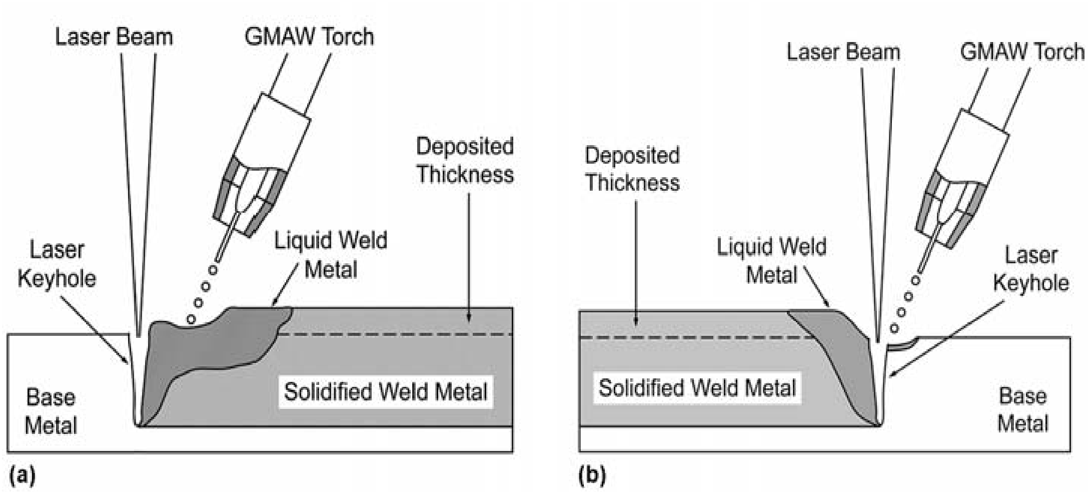


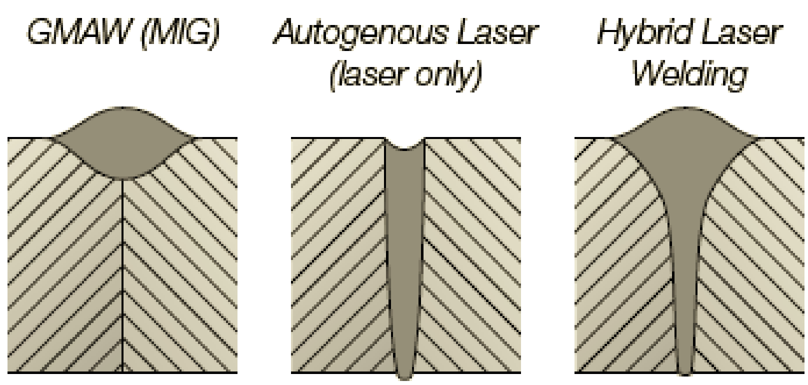
**Fig.4.1 Laser Hybrid Welding Equipment (Laser-TIG) [20]**

There are two possible situations; one in which laser welding source move ahead of arc welding source and the other in which arc welding source move ahead of laser welding source. The two scenarios are shown in Fig 4.2.




Schematic of hybrid laser arc welding process orientations. (a) Laser leading. (b) Arc leading. GMAW, gas metal arc welding

**Fig. 4.2 Schematic of Hybrid Laser Arc Welding process [22]**




*Graphic illustrating differences between GMAW, Laser and Hybrid Laser Welding weld profiles*

**Fig. 4.3 Graph showing advantage of Hybrid Laser-GMAW process [22]**

The advantage of combining arc welding process and laser welding process results in an increase in both the depth of penetration and speed of welding as shown in Figure 4.3. The metal vapors trying to escape from vapor cavity acts upon the plasma arc. Absorption of laser radiation in the arc processing is negligible. The nature of the overall hybrid welding process can be determined primarily either by arc or by the laser, depending upon the two power input ratios. The temperature of the metal surface has significant influence on the absorption of the laser radiation. Therefore the initial reflectance must be overcome before the start of laser welding process especially on aluminum surfaces. Pre-heating the metal serves the purpose. In the hybrid welding process, the arc provides initial heat to the work-piece, later the laser beam joins in. Vapor cavity is formed after the vaporization temperature has been reached and nearly all radiation energy without lose can be put into the metal under welding. The total energy required is equal to energy for the temperature-dependent absorption and energy lost by conduction into the rest of the work-piece. In Hybrid laser MIG welding, vaporization occurs from the surface of the work-piece and the filler wire, so absorption of laser is more facilitated by extra available metal vapors due to filler wire.

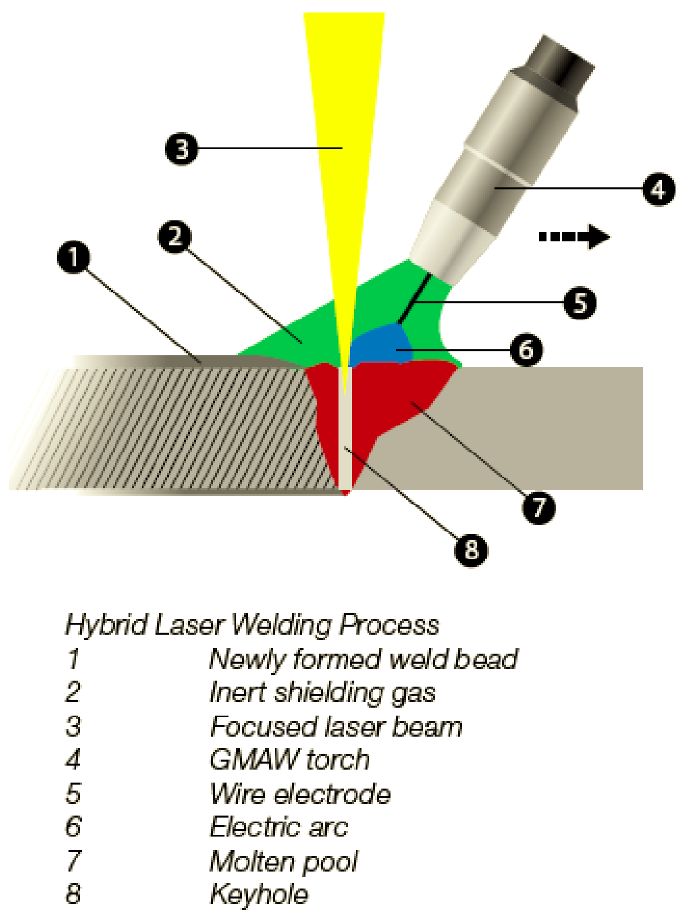
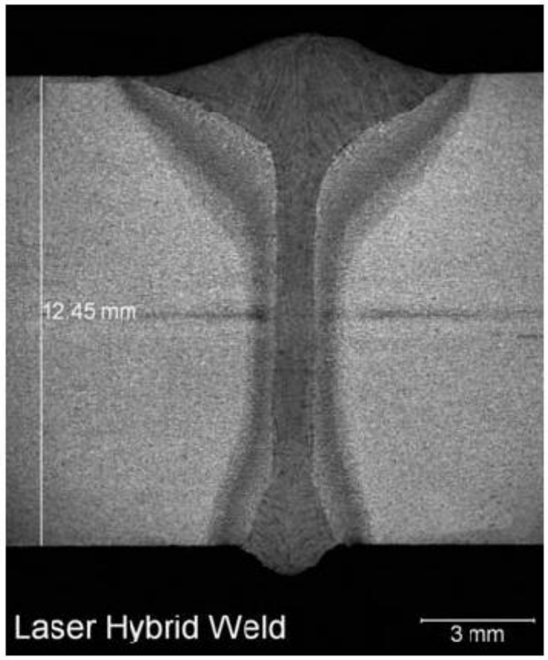



**Fig.4.4 Schematic illustration of Laser-Arc Hybrid welding [28]**




Cross section of hybrid laser arc welding on a carbon steel square butt joint. Courtesy of Edison Welding Institute

**Fig. 4.5 Hybrid Laser-Arc Welded Joint**

Hybrid laser arc welded joint is shown in figure 4.5. Here 13mm weld joint is made with hybrid welding process with small thickness weld bead and small Heat Affected Zone.

## 4.3 APPLICATIONS OF MULTI-PROCESS WELDING

Through multi-process welding improved weld quality can be achieved at the same time along with higher welding speeds. The multi-process welding improves the weld quality, affirms weld penetration and reduces thermal distortion of the welded metal.

Multi-process welding is enjoying ever greater popularity and is currently being used in other branches, like rail vehicle manufacturing, crane construction, truck production, thin walled cylinders, pressure vessels, and in heavy industry.

The chief benefits of multi-process welding can be summarized.

- Relaxed tolerance for the joint: for example, hybrid welding can relax the tolerance for the joint fit-up by a factor of at least 2-3 over laser welding or greater with adaptive control of welding parameters.

- Improved weld quality: weld quality can be improved due to reduction in prosity with respect to other welds.
- Increases in welding speed: Hybrid welding shows that considerable increase in speed is possible with these processes.
- The Increase in welding speed and depth of penetration in the work-piece are desirable and important. Because reduced heat input results in less HAZ which reduces weld distortions.

# CHAPTER 05
# RESEARCH METHODOLOGY

## INTRODUCTION

This chapter describes practical implementation of multi-process welding procedure. The multi-process welding technique is applied to the weld joint and dual welding (EBW+TIG Welding) approach is adopted. In this research work, Electron Beam Welding process and TIG welding process are adopted for the welding of HSLA steel. HSLA steels are the steels having carbon %age as low as 0.3 ~ 0.5 % **[23]**. These steels can be hardened by heat-treatment (Quenching and tempering). They attain strength by quenching and tempering. The major applications include high pressure applications, aerospace &aircraft applications, ship building, industrial applications etc.

The dual welding (EBW+TIG Welding) process differs little bit from hybrid welding process, as in dual welding (EBW+TIG Welding) two welding processes are not applied simultaneously in the same molten pool.

A dual process (EBW+TIG welding) is a welding process where two separate weld processes act in a row. First one welding process (EBW) is being carried out, and then the second welding process (TIG) is done on already completed welding process. After welding, heat-treatment is carried out to increase the mechanical properties of the samples.

## 5.1 OBJECTIVES OF RESEARCH

The purpose of the present efforts was to investigate the dual welding process on HSLA steel. The comparison is made, after tensile testing of welded work-piece samples, between the mechanical properties of individual welding processes (EBW & TIG) and dual welding process (EBW+TIG Welding). We have lot of data published about the research done on the individual welding processes such as (TIG, Plasma, laser, Friction stir & EBW machines) but very limited data published w.r.t. dual welding process (EBW+TIG Welding)

In hybrid welding process, two welding processes act simultaneously, and welding is done in the same molten pool **[23]**. Dual welding (EBW+TIG Welding) differs from hybrid welding in the sense that two welding processes act in succession i.e. after one another. In this dissertation, we selected two welding processes. One is Electron Beam Welding (EBW) and the other is TIG Welding process.

## 5.2. SELECTION OF MATERIAL FOR RESEARCH

High Strength Low Alloy steels offer excellent mechanical properties, and excellent resistance to atmospheric corrosion. Major applications of HSLA steels includes Aerospace, High pressure applications, Aircraft industry, and Conventional Industrial applications. The HSLA steels have excellent formability due to low carbon and the percentage of carbon in these steels lie between 0.3-0.5% and the basic alloying elements are Ni, Cr, Mo and V **[23]**. The steel hardness can be increased by heat-treatment cycles (Quenching and Tempering). After heat-treatment cycles, these steels may attain strength of up to 1800 MPa. Because of carbon and alloying elements, these steels are prone to cold cracking phenomenon. Pre-heat is necessarily required for such steels before welding. Stress relieving is necessary after welding to prevent cracking.

The chemical composition of the HSLA steel as provided is as shown in Table 5.1

**Table- 5.1**

**Chemical Composition of Material**

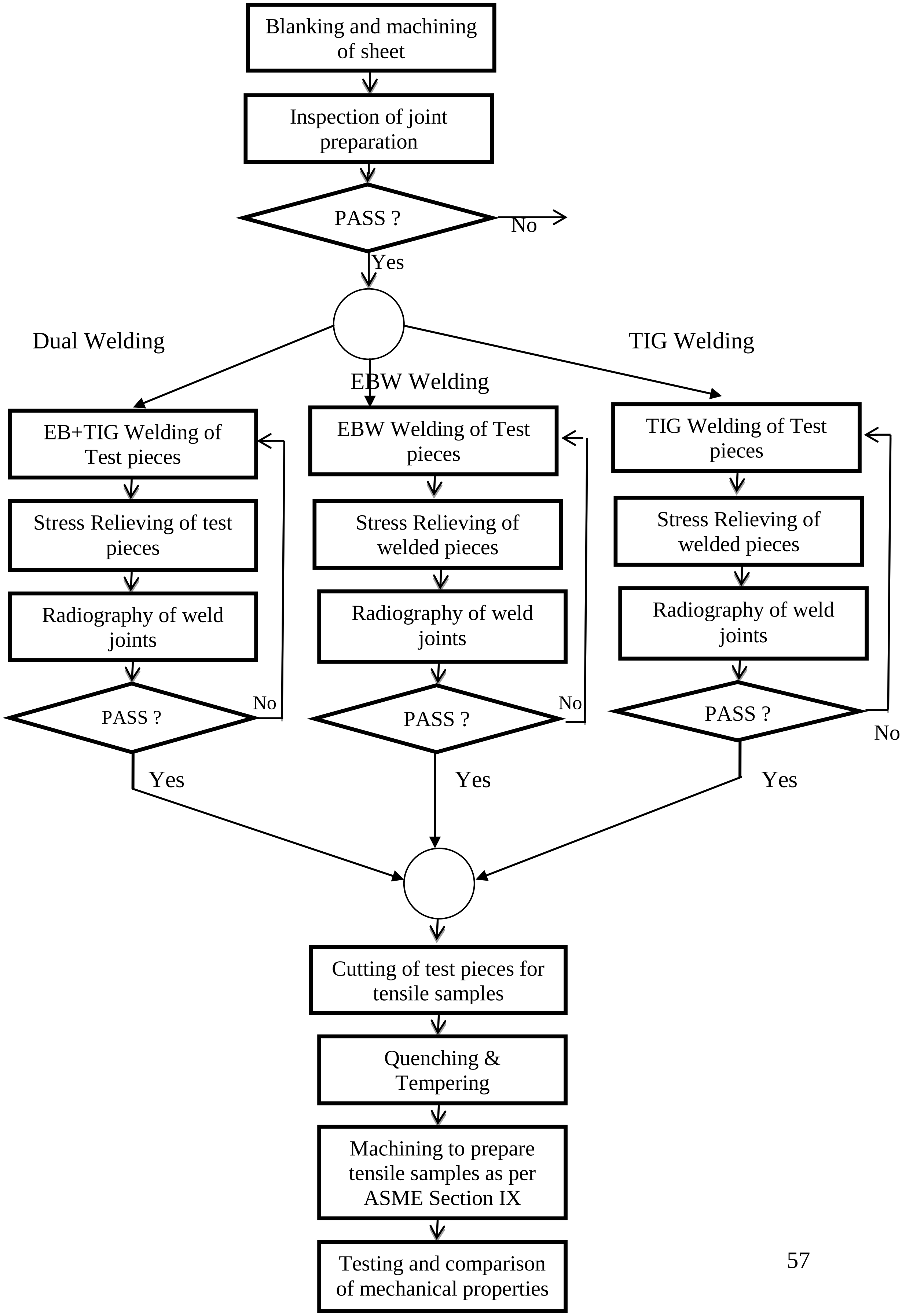
| C | Mn | P | S | Si | Cr | Ni | Mo | V |
|---|---|---|---|---|---|---|---|---|
| 0.28~0.32 | 0.7~1.0 | ≤0.01 | ≤0.013 | 1.5~1.7 | 1.0~1.3 | 0.25 | 0.4~0.55 | 0.08~0.15 |

The chemical composition of filler wire used for welding is shown in Table 5.2

Table 5.2 Chemical composition of Filler Wire (H08)

| | C | Cr | Si | Mn | V | Mo | Ni | P | S | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Content (%) | 0.08-0.12 | 1.4-1.7 | 1.1-1.3 | 0.9-1.1 | 0.05-0.15 | 0.4-0.6 | 1.8-2 | ≤ 0.006 | ≤0.005 | ≤0.10 |

## 5.3 FLOW CHART OF PROCESS



## 5.4 THICKNESS SELECTION

The sheet metal of thickness 4.5 +0.2, -0 mm was selected. Some surface defects and scratches were removed with emery flap disc while ensuring the minimum required thickness. A set of welding test coupon were processed. This thickness was measured at different locations of test coupons and no significant thickness variation is observed.

## 6.5 EXPERIMENTAL PROCEDURE

### 5.5.1 PARAMETER FINALIZATION

Welding parameters are required to be finalized before starting the welding process on the actual test coupons. Some plates of metal to be welded were provided to the welder for the finalization of parameters. These parameters vary with variation of thickness of metal.

### 5.5.2 PREPARATIONS FOR WELDING

HSLA steel sheets (base metal) were arranged and were cut by sheering process. The chemical composition of sheets was as shown in Table 5.1.

Test pieces to be welded are prepared for welding. For TIG Welding, welding bevel is required as filler wire is used in this process. The same material filler wire is used in this work. For EB Welding, Face of the metal to be welded must be flat and there should be no gap between matting faces to be welded. This face is machined for this purpose. Filler metal is not required in case of EB Welding. All the test pieces are chemically cleaned before welding to avoid contamination. The test pieces are de-magnetized before welding in EBW machine.

### 5.5.3 WELDING PROCESS

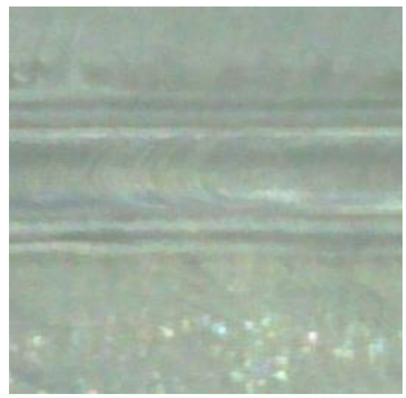
We have prepared three types of test pieces: TIG Welded, EB Welded and EB-TIG Welded. These are required for the comparison of mechanical properties achieved. All these test coupons were stress relieved after each welding process to avoid cracking.

Dual welded test coupons, First the test pieces ware welded by EB Welding process and later the same welded test pieces was reinforcement welded on Top and Bottom of EB welds after proper cleaning and stress relieving.

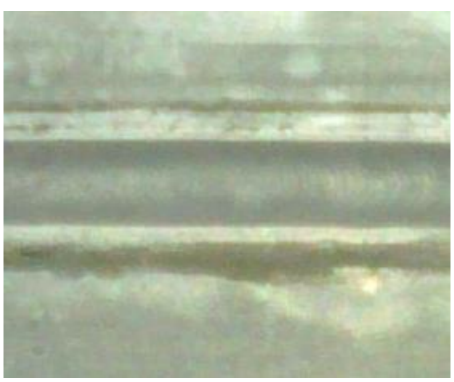
EB Welded (Top Side)

EB Welded (Bottom Side)

TIG Welded (Top Side)



TIG Welded (Bottom Side)



EB-TIG Welded (Top Side)

EB-TIG Welded (Bottom Side)

**Fig.5.2 EB, TIG, Dual welded test coupon specimen**

The clamping fixturing arrangement of test coupon on automatic TIG welding machine is shown in Fig. 4.3. Similar types of fixtures were used on EBW machines.

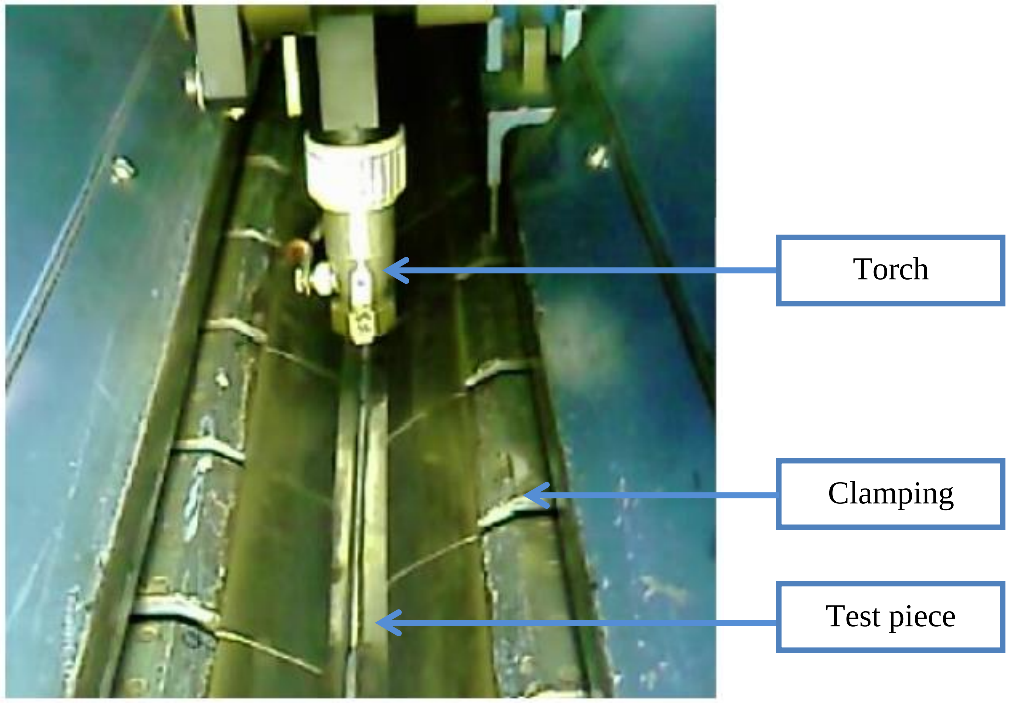



**Fig. 5.3 Automatic TIG welding**

The as welded test coupon after welding on machine is shown in Fig. 5.4

**Fig.5.4 TIG welded Test coupon after welding on machine**

### 5.5.4 RADIOGRAPHIC TESTING

For welding qualification, international welding standards ASME Section IX and British standard BS EN ISO 13919-1 are followed for TIG and EB welding respectively. Usually for ferrous materials weld quality of EB is higher than TIG due to weld pool formation under vacuum, whereas in case of TIG porosity cannot be eliminated completely due to shielding gas entrapment. In this work EB-TIG joint was found mostly defect free and qualified in Class I (ASME Section IX). All the welds produced by TIG and EB were also qualified by Radiography in Class I.

### 5.5.5 HEAT-TREATMENT PROCESS

Now blanks for tensile sample were cut from test coupons for Tensile samples preparation before heat-treatment because after heat-treatment machining becomes difficult as HSLA steels achieve hardness up to 55 HRC. The remainder material after cutting blanks is as shown in Fig. 5.5

**Fig. 5.5 Remainder of test coupon after cutting of sample blanks**

Now these tensile sample blanks were processed for strengthening treatment. Hardening followed by tempering process was done to refine the mechanical properties according to our requirement as shown in Table-5.3.

| Table 5.3<br>Required Mechanical Properties | | | |
|---|---|---|---|
| **Tensile Strength MPa** | **Yield Strength MPa** | **% Elongation** | **Hardness HRc** |
| ≥ 1600 | ≥ 1300 | ≥ 7 | ≥ 48 |

To achieve the above cited properties, heat-treatment was done as per following procedure.

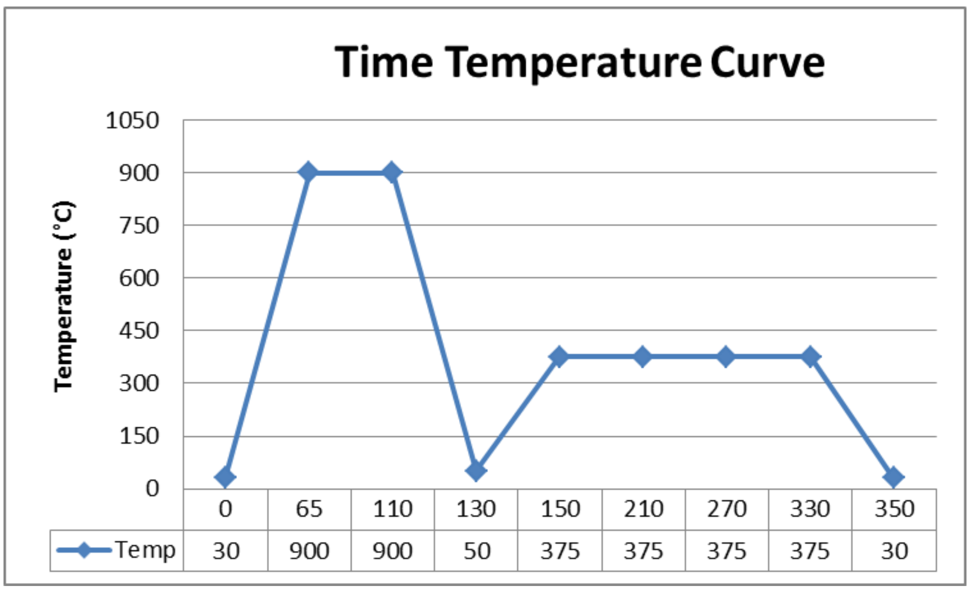



**Figure-5.6 : Time Vs Temperature Curve for Hardening and Tempering**

The hardening and tempering was done in accordance with the Time-Temperature curve as shown in Figure-5.6. In initial phase the job was shifted in the furnace at room temperature. Temperature was raised to 900$^{o}$C in 65 minutes. Then the job was held in furnace at 900$^{o}$C for forty five minutes (holding time) and after that job was oil quenched for 20 minutes. In 3$^{rd}$ phase the job was tempered at 375$^{o}$C for three hours. The job was air cooled after tempering.

The mechanical properties of the base metal achieved after hardening and tempering were tested latter and were found to be within the level of acceptance as per requirement. Normally welded samples as per ASME IX standard are used for weld qualification of Boilers and pressure vessels and same sampling standard is adopted for this work qualification which gives ultimate tensile strength of the weld-ment in available gauges.

### 5.5.6 TENSILE SAMPLE PREPARATION & TESTING

ASME section IX was followed in this research work for preparation of welded samples. After Heat-treatment these rectangular blanks were machined to prepare tensile samples. The machined tensile samples were tested in testing lab. The tensile testing machine arrangement is as shown in Figure 5.7

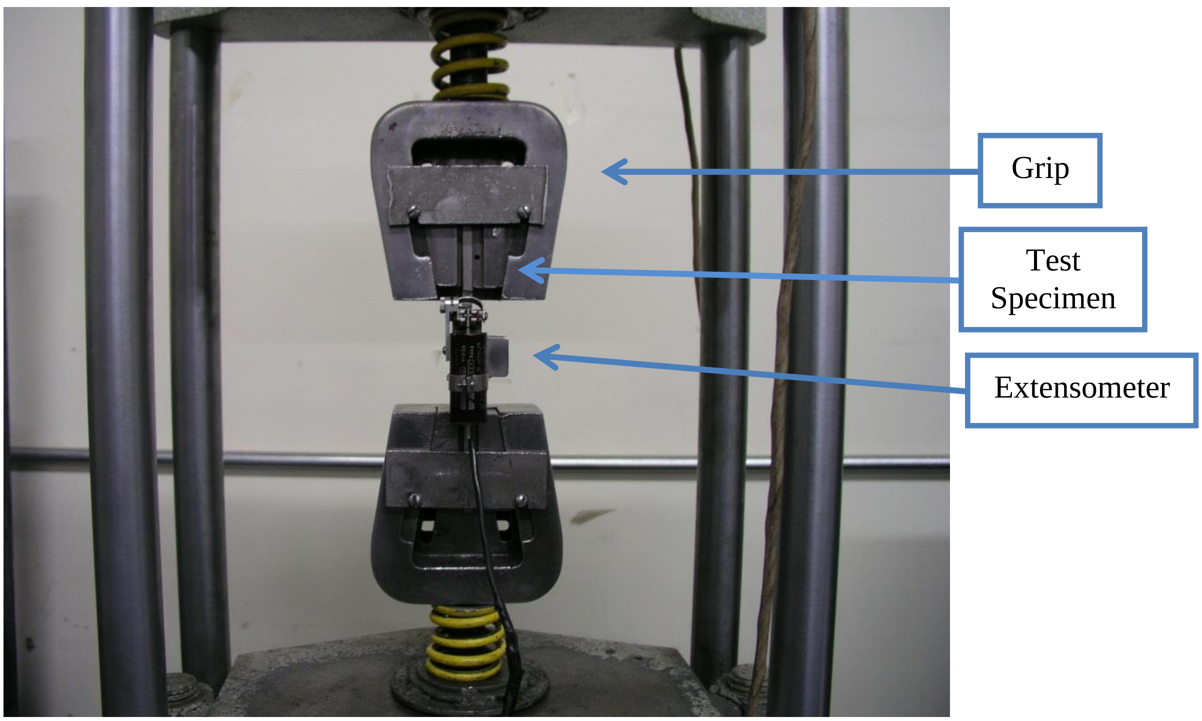



**Fig.5.7 Tensile Testing Equipment**

The machined tensile samples and tested tensile samples are shown in the Figure 5.8 & Figure 5.9. The fracture of the tensile sample is from base metal, away from the weld bead and HAZ.

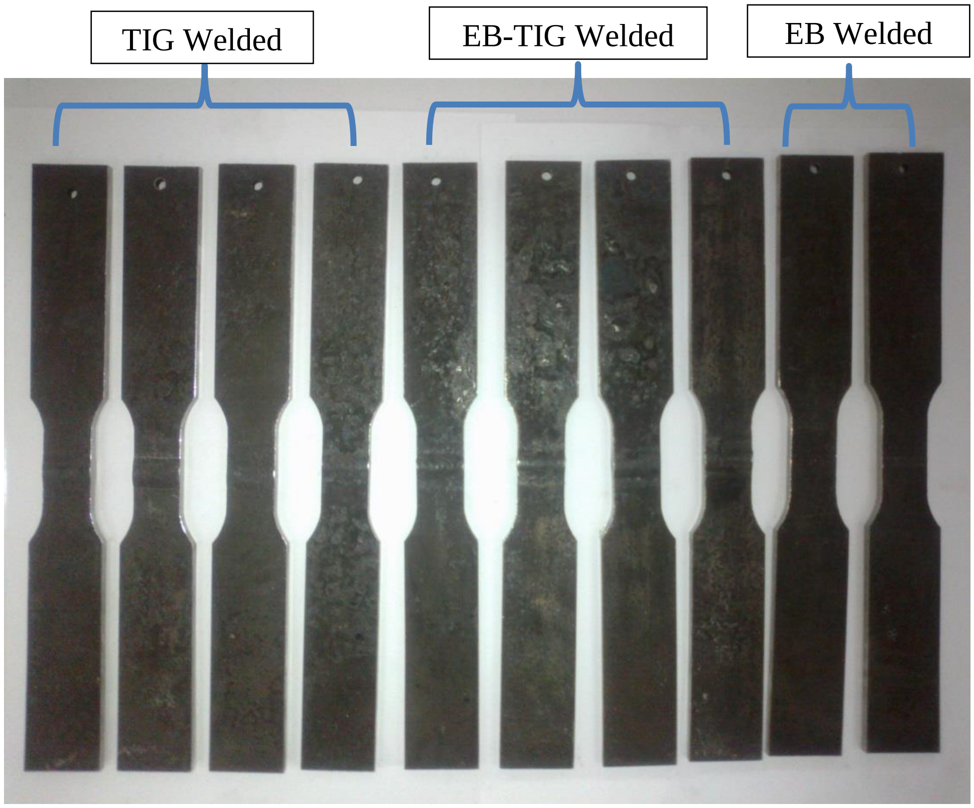



**Fig. 5.8 Machined Tensile Samples**

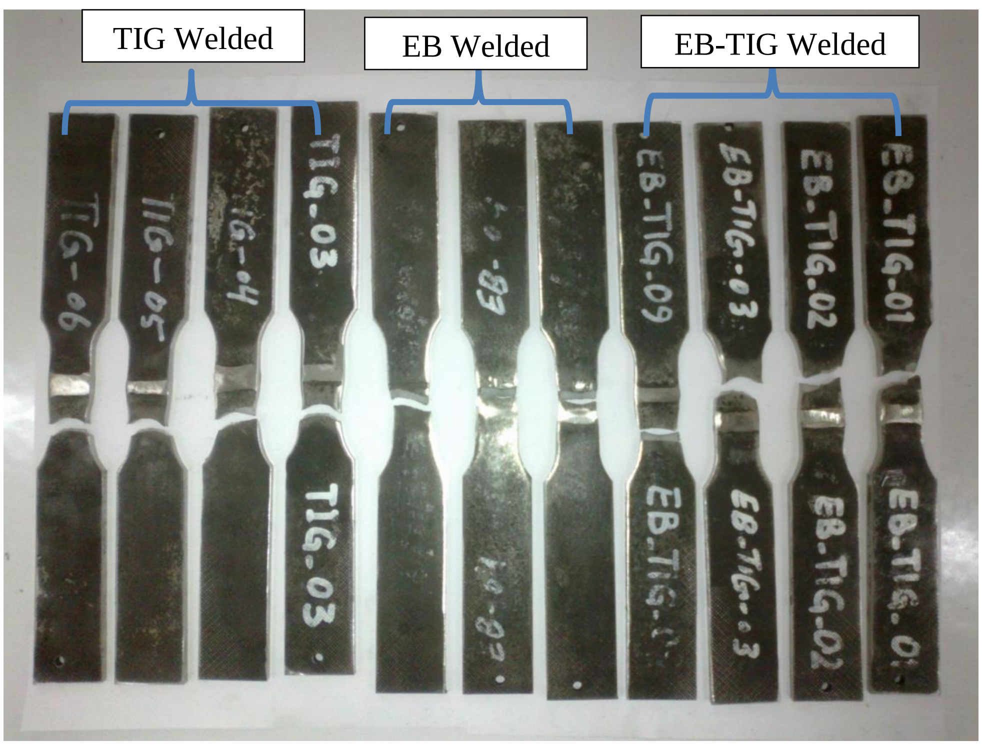



**Fig. 5.9 Tensile Samples after testing**

The results obtained after testing are discussed in next chapter.

# CHAPTER 6
# RESULTS AND DISCUSSIONS

## INTRODUCTION

In this chapter, we discussed about the results obtained from mechanical testing the samples and a comparison will be made between different welding processes results. Further the microstructure of all the samples was checked and discussed. At the end, future research topics are suggested.

## 6.1 COMPARISON OF MECHANICAL PROPERTIES

The major mechanical properties are Ultimate tensile strength, Yield strength and percentage elongation and hardness of the work-piece. All these properties are now discussed one by one (As welded and after Quenching and Tempering).

### 6.1.1 TENSILE STRENGTH

The tensile strength obtained from experiments is mentioned in the table 6.1

**Table 6.1 Tensile Strength of the welded samples after Experimentation**

| Condition | Process | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Welded | EB | 748 | 755 | 769 | 770 | 741 | 744 | 737 | 761 | 760 | | | 753.8889 |
| | EB-TIG | 765 | 780 | 788 | 750 | 769 | 772 | 766 | 754 | 758 | | | 766.8889 |
| | TIG | 725 | 743 | 736 | 733 | 731 | 742 | 737 | 738 | 735 | | | 735.5556 |
| Quenched & Tempered | EB | 1698 | 1717 | 1681 | 1693 | 1703 | 1739 | 1714 | 1676 | 1743 | 1621 | 1710 | 1699.55 |
| | EB-TIG | 1746 | 1739 | 1763 | 1705 | 1757 | 1692 | 1744 | 1692 | 1725 | 1712 | 1734 | 1728.09 |
| | TIG | 1664 | 1697 | 1601 | 1634 | 1689 | 1623 | 1678 | 1630 | 1695 | 1612 | 1635 | 1650.73 |

Average tensile strength (As Welded) of EB, EB-TIG and TIG is 753, 766 and 535 MPa respectively. Average tensile strength (Q & T) of EB, EB-TIG and TIG is 1699, 1728 and 1650 MPa respectively.

The standard deviation error bar comparison of the tensile strength (as welded and Quenched & Tempered) are shown in Figure-6.1

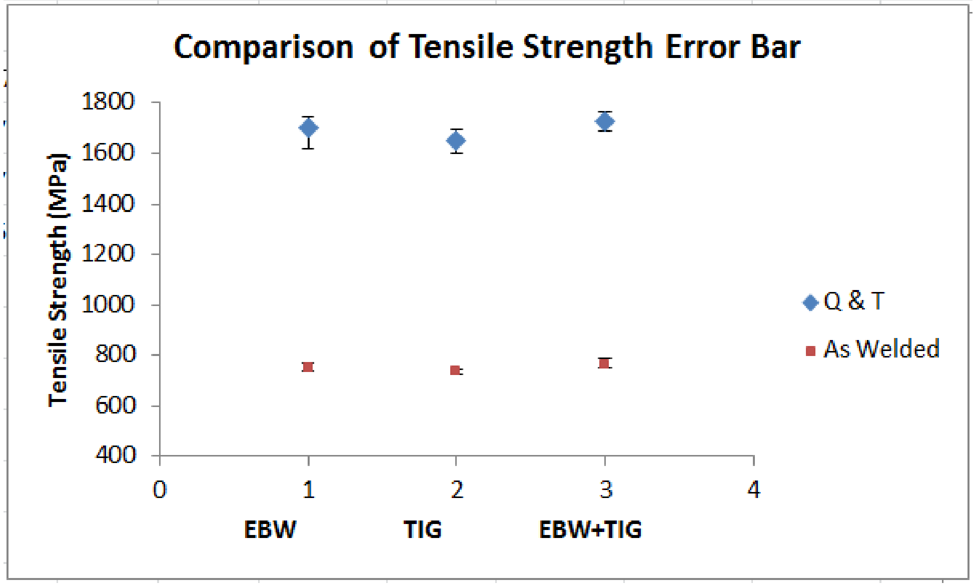



**Fig. 6.1 Comparison of Tensile strength STD Dev. Error Bar**

## 6.1.2 YIELD STRENGTH

The yield strength obtained from experiments is mentioned in the table 6.2

**Table 6.2 Yield Strength of the welded samples after Experimentation**

| Condition | Process | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Welded | EB | 525 | 510 | 530 | 512 | 528 | 529 | 531 | 515 | 518 | | | 522.00 |
| | EB-TIG | 535 | 546 | 555 | 560 | 552 | 533 | 555 | 538 | 561 | | | 548.33 |
| | TIG | 488 | 505 | 499 | 511 | 493 | 491 | 505 | 484 | 510 | | | 498.44 |
| Quenched & Tempered | EB | 1340 | 1396 | 1401 | 1412 | 1375 | 1423 | 1370 | 1356 | 1368 | 1380 | 1388 | 1382.64 |
| | EB-TIG | 1348 | 1405 | 1394 | 1418 | 1388 | 1410 | 1352 | 1397 | 1385 | 1391 | 1402 | 1390.00 |
| | TIG | 1325 | 1350 | 1354 | 1369 | 1351 | 1372 | 1329 | 1360 | 1371 | 1343 | 1368 | 1353.82 |

Average yield strength (As Welded) of EB, EB-TIG and TIG is 522, 548 and 498 MPa respectively. Average yield strength (Q & T) of EB, EB-TIG and TIG is 1382, 1390 and 1353 MPa respectively.

The standard deviation error bar of the yield strength (as welded and Quenched & Tempered) are shown in Figure-6.2

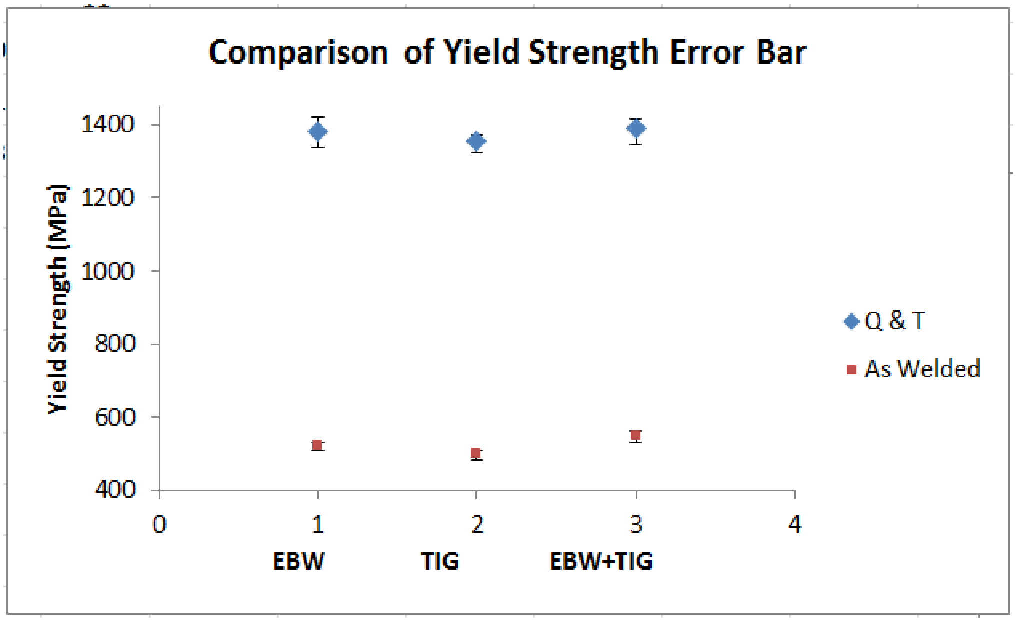



**Fig. 6.2 Comparison of Yield strength STD Dev. Error Bar**

## 6.1.3 PECENTAGE ELONGATION

The %age elongation obtained from experiments is mentioned in the table 6.3

**Table 6.3 %age Elongation of the welded samples after Experimentation**

| Condition | Process | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Welded | EB | 17 | 17 | 16 | 17 | 17 | 16 | 17 | 17 | 16 | | | 16.67 |
| | EB-TIG | 16 | 17 | 17 | 16 | 17 | 16 | 17 | 16 | 17 | | | 16.56 |
| | TIG | 17 | 16 | 16 | 17 | 16 | 16 | 17 | 16 | 16 | | | 16.33 |
| Quenched & Tempered | EB | 12 | 10 | 14 | 14 | 11 | 15 | 10 | 8 | 9 | 9 | 10 | 11.09 |
| | EB-TIG | 10 | 9 | 15 | 9 | 8 | 12 | 11 | 10 | 12 | 9 | 15 | 10.91 |
| | TIG | 9 | 11 | 9 | 8 | 13 | 10 | 9 | 12 | 8 | 11 | 9 | 9.91 |

Average %age elongation (As welded) of EB, EB-TIG and TIG is 16.6, 16.5 and 16.3 respectively. Average %age elongation (Q & T) of EB, EB-TIG and TIG is 11, 10.9 and 9.9 respectively.

The standard deviation error bar of the %age elongation (as welded and Quenched & Tempered) are shown in Figure-6.3

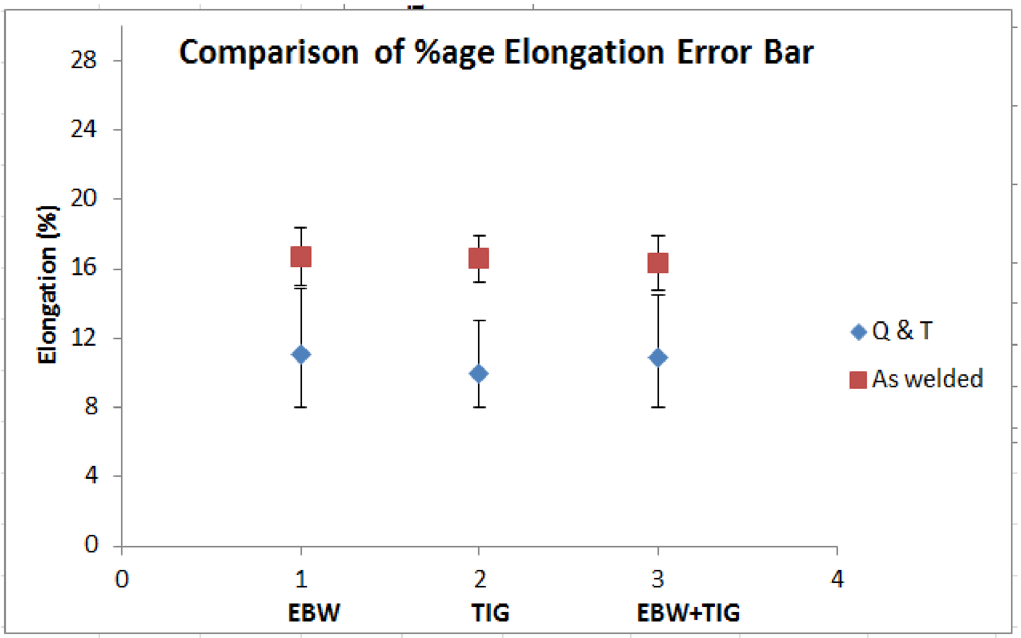



**Fig. 6.3 Comparison of Elongation STD Dev. Error Bar**

## 6.1.4 HARDNESS

The Hardness obtained from experiments is mentioned in the table 6.4

**Table 6.4 Hardness of the welded samples after Experimentation**

| Condition | Process | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Welded | EB | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | | | 20.00 |
| | EB-TIG | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | | | 20.00 |
| | TIG | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | | | 20.00 |
| Quenched & Tempered | EB | 50 | 49 | 49 | 50 | 48 | 52 | 49 | 51 | 49 | 48 | 50 | 49.55 |
| | EB-TIG | 52 | 50 | 49 | 54 | 49 | 49 | 51 | 53 | 48 | 52 | 51 | 50.73 |
| | TIG | 48 | 49 | 50 | 50 | 49 | 50 | 53 | 48 | 52 | 51 | 50 | 50.00 |

Average Hardness (Q & T) of EB, EB-TIG and TIG is 49.5, 50.7 and 50 respectively. The hardness of Base metal was 20 HRC.

The standard deviation error bar of the hardness (as welded and Quenched & Tempered) are shown in Figure-6.3

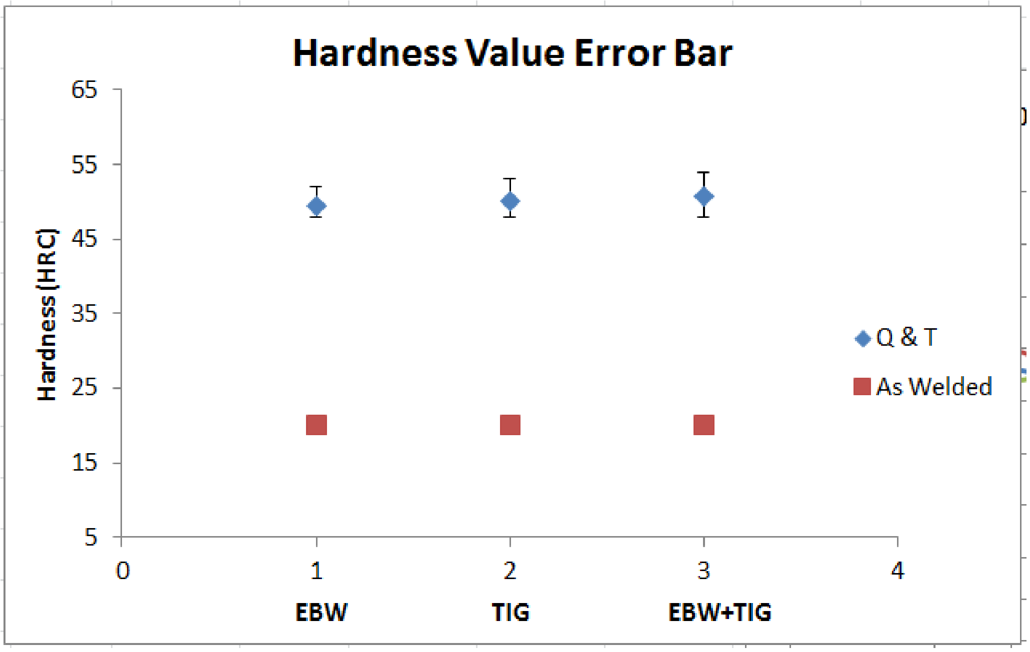



**Fig. 6.4 Comparison of hardness STD Dev. Error Bar**

## 6.2 MICRO-STRUCTURE ANALYSIS

### 6.2.1 TIG WELDED SAMPLE

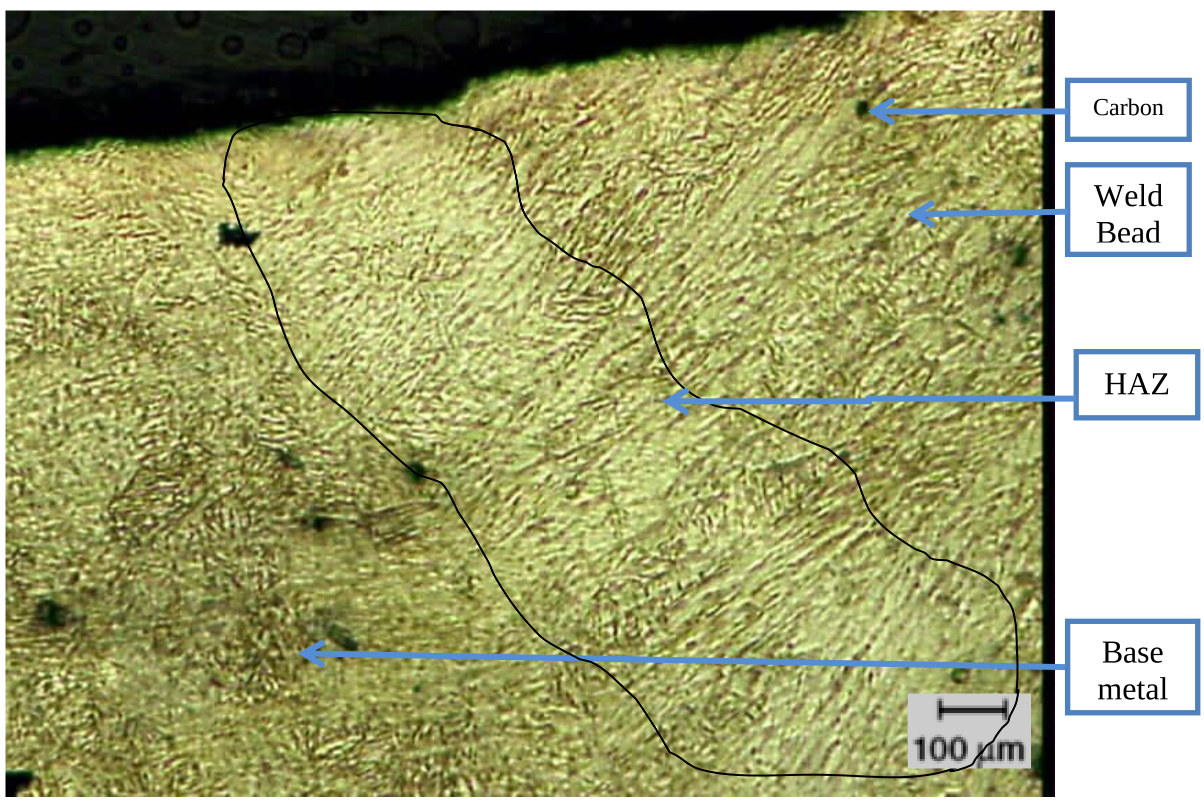



**Fig. 6.5 Micrograph of TIG welded Sample stress relieved (50 X)**

## 6.2.2 EB WELDED SAMPLE

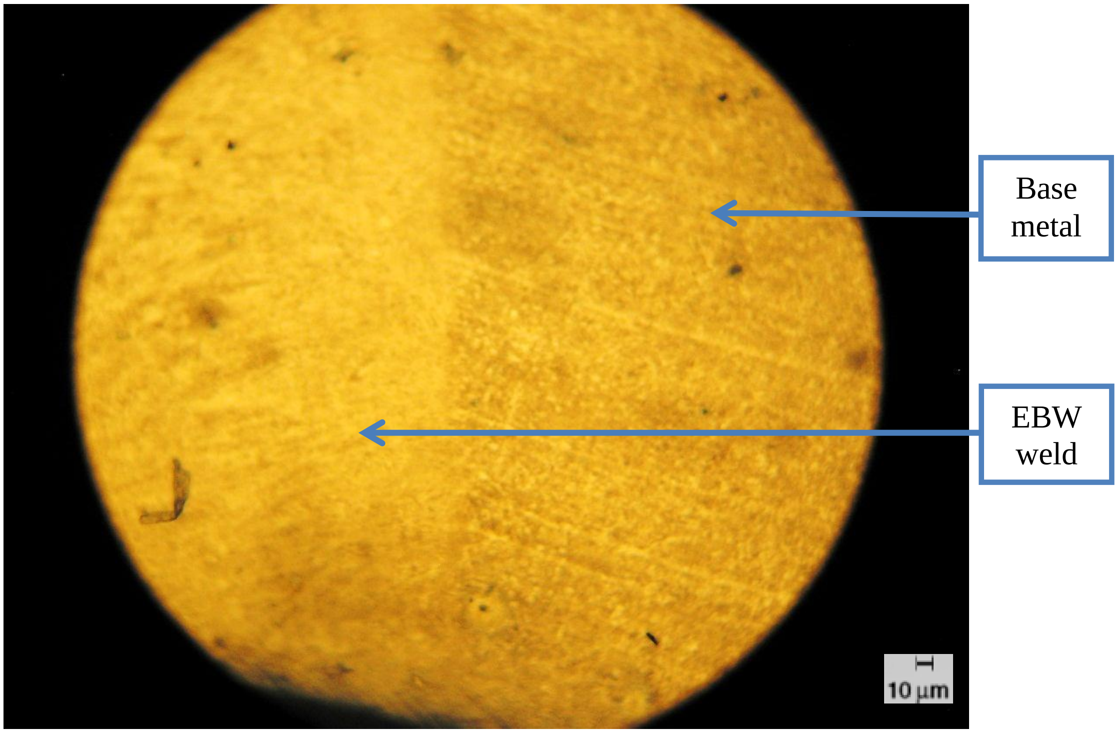



**Fig. 6.6 Micrograph of EB Welded Sample Stress Relived (200X)**

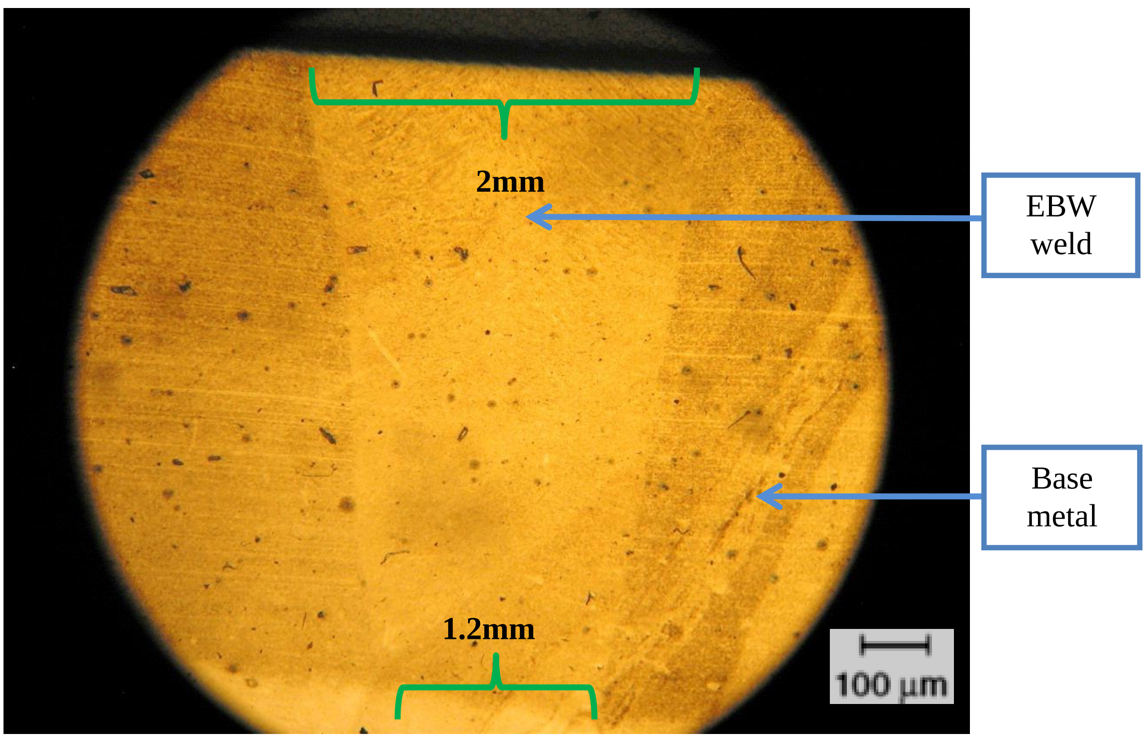



**Fig. 6.7 Micrograph of EB welded Sample Quenched & Tempered (50 X)**

Fig. 6.7 shows the micrograph of electron beam welded sample after quenching and tempering. Very fine martensitic structure is visible in conical shape EB welded zone as compared to base metal. Micro hardness measured which is 51.3 at EB region almost same as that of base metal which is 52 HRC. Melting pool is very sharp due to very small beam diameter, high power density (in mw) and fast feed rate.

### 6.2.3 EB-TIG WELDED SAMPLE

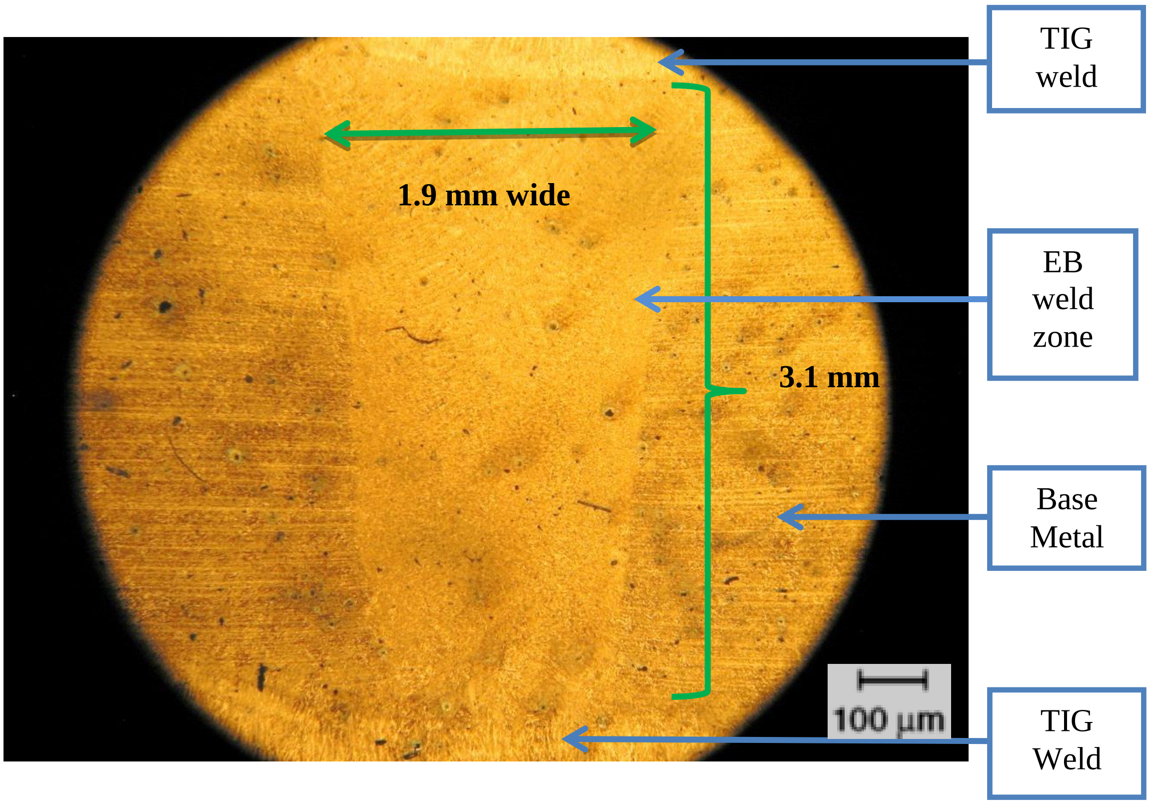



**Fig. 6.8 Micrograph of EB-TIG Welded Sample Q&T (50X)**

Figure 6.8 shows the quench tempered micrograph of EB-TIG welded sample. Tempered martensitic structure is observed throughout the sample both in weld zone and base metal. The interfaces of EB-TIG weld zone and base TIG / EB weld zone is distinct. In the upper and lower TIG welded region coarse tempered martensitic microstructure is observed. Whereas the center weld region fine martensitic structure is formed as compared to base metal due to high welding speed (3 times) as compared to TIG welding. Micro-Hardness measured in EB welded region is 53.5 same as that of base metal (54), however in TIG welded region, hardness is 49.5 slightly lower than base metal due to coarse martensitic microstructure. EB welded zone is reduced from 4.5 mm to 3.1 mm due to TIG welding on both sides of EB welded zone.

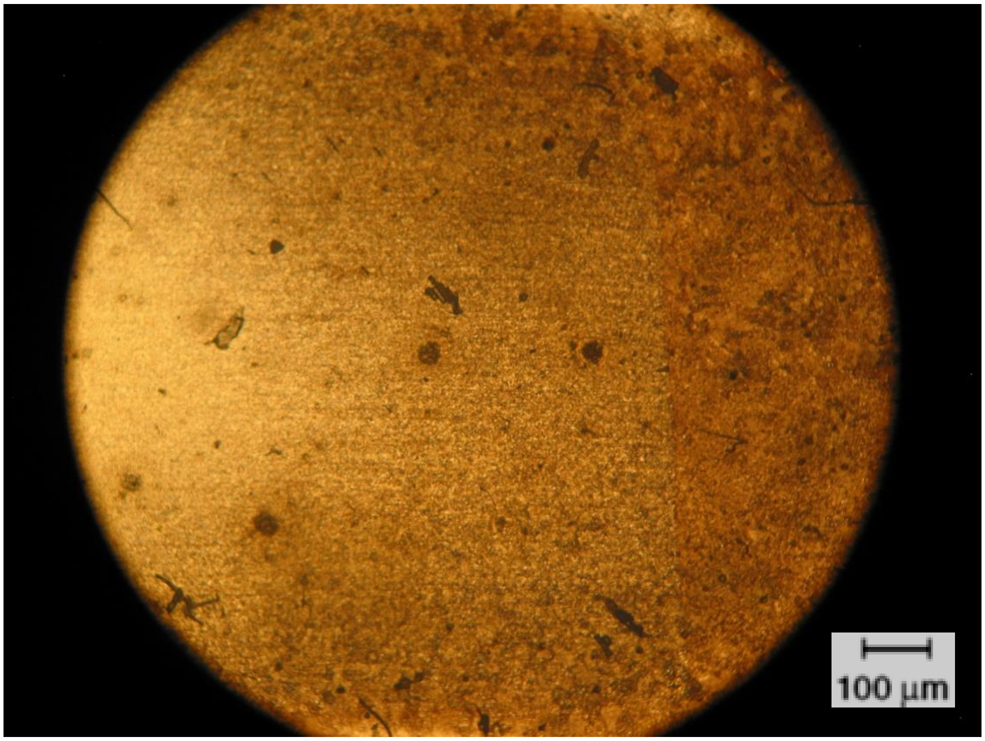



**Fig. 6.9 Micrograph of EB -TIG Stress Relieved welded sample (50 X)**

## 6.3 DISCUSSIONS ABOUT THE RESULTS

The results obtained from the experiments are compared with respect to mechanical properties (both as welded and quenched and tempered). It is clear from these results that EBW Welding Process and Dual welding (EBW+TIG) process have almost the same results, though the dual welding (EBW+TIG) process shows small lead in the results with respect to tensile strength, yield strength, percentage elongation and hardness. Only in one or two cases the EBW welding process results are higher than dual welding (EBW+TIG) process. The results of dual welding (EBW+TIG) with respect to other two welding processes (EBW & TIG) are positive in the sense that before experiments, we thought the EB welding process might have better results than dual welding (EBW+TIG) process. Special applications from dual welding (EBW+TIG) process can be achieved for aerospace, high pressure vessels, aircraft industry.

The TIG welding process, though passed the laid criteria for qualification, yet the results have lower value than the other two processes. This was also expected from the beginning that TIG welding process will show low properties with respect to other processes. This was because of the large Heat Affected Zone, large Fusion Zone and stress concentration. These factors contributed and degraded the mechanical properties of the TIG welded test sample.

## 6.4 FUTURE RESEARCH PROPOSALS

The comparison of mechanical properties of Dual welded and Hybrid Laser-TIG welded tensile samples. Fatigue analysis and life prediction of dual or hybrid weld joints has become more important and is the subject of ongoing research.

# REFERENCES

[1] Qureshi, M. Ejaz., 2008. Analysis of Residual Stresses & Distortions in cirucumferentially welded thin walled cylinders. Thesis (PhD). NUST Islamabad.

[2] O.W. Blodgett. Distortion: How to minimize it with Sound Design Practices and Controlled Welding Procedures plus Proven Methods for Straightening Distorted Members, pp. 1–19, The Lincoln Electric Company, G261

[3] H.D. Hibbitt and P.V. Marcal. A Numerical Thermo-mechanical Model for the Welding and Subsequent Loading of a Fabricated Structure. Journal of Computers and Structures 1973; 3:1153–1174.

[4] Z. Feng and O. Ridge. Processes and Mechanisms of Welding Residual Stress and Distortion. Woodhead Publishing Limited, 2005.

[5] James, F., The Procedure Handbook of Arc Welding, 14th edition. Lincoln Arc Welding Foundation, Cleveland, USA, 2000.

[6] Welding Handbook, Volume 1, Eighth Edition; L. P. Connor; American Welding Society, Miami, FL; 1987.

[7] ASM Handbook (Welding, Brazing and Soldering). Vol. 6, pp.190.

[8] Internet source https://en.wikipedia.org

[9] Internet source https://en.wikipedia.org/wiki/Electron_beam_welding

[10] Internet Source ttp://www.ewf.be/media/documentosdocs/doc_87_technical_sheet_-_tig_welding.pdf

[11] Gas Tungsten Arc Welding-GTAW-(40 Hour Course). German Development Service,2000.

[12] Guide to TIG Welding. RTech Welding Equpment,2009.

[13] Miller. Guidelines for Gas Tungsten Arc Welding (GTAW). Miller welds,2013.

[14] Weldability. Introduction to TIG Welding. Weldability.com

[15] Weldwell. TIG Welding Booklet. Weldwell, Newzealand, Napier.

[16] Electron Beam Welding-chapter 9. Internet Source www.kau.ac.kr

[17] Internet source http://www.ewf.be/media/documentosdocs/doc_26_electron_beam_welding.pdf

[18] Internet source https://en.wikipedia.org/wiki/Electron_beam_welding
[19] Dr. G. Schubert. Electron Beam Welding-Process, Application and Equipment. PTR Precision Technologies Inc.
[20] Internet source http://www.twi-global.com/capabilities/joining-technologies/lasers /hybrid-laser-arc-welding/
[21] Internet source http://www.trumpf-laser.com/en/solutions/applications/laser-welding/hybrid-welding.html
[22] Internet source http://www.kuka-systems.com/en/technologies/exhibition_hybrid/
[23] Internet source https://en.wikipedia.org/wiki/tig_welding.html
[24] Internet source http://cswipquestions.blogspot.com/2014/07/migmag-welding-gmaw-process.html
[25] Internet source http://www.zoombd24.com/arc-welding/
[26] Internet source http://www.ptreb.com/Electron_Beam_Welding_Technical_Papers /Electron_Beam_Welding_Process_Applications_and_Equipment/
[27] Internet source http://www.joiningtech.com/industry-references/welding-types/electron-beam-welding
[28] Internet source http://www.esab.com/hlaw/process/