Investigation into Electron Beam Welding (EBW) of High Strength Alloys

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ISLAMABAD

August 2021

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Mechanical Engineering

Thesis Supervisor:

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August, 2021

Declaration

I certify that this research work titled "*Investigation into Electron Beam Welding of High Strength Steel Alloy*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Acknowledgements

I am thankful to my Creator **Allah Subhana-Watala** to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor **Dr. Sayyed Hussain Imran Jaffery** for his help throughout my thesis and his patience, motivation help and immense knowledge. His guidance helped me in all the time of research and writing of this thesis

I would also like to pay special thanks to **Dr. Mushtaq khan**, **Dr. Amir Mubashir** and **Dr. Sajid Yaqub** for their tremendous support and cooperation. Each time I got stuck in something, I was offered help and guidance from these experienced professionals. Without their help I wouldn't have been able to complete my thesis. I appreciate their patience and guidance throughout the whole thesis.

Last but not the least, I would like to thank my family for their never ending support and encouragement through very difficult times to complete research work. Especially my **mother** and **father** who pray for me every second.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents and adored siblings

Whose tremendous support and cooperation

led me to this wonderful accomplishment.

&

To my Respected Teachers,

Who acted like compass

that activated the magnets of

curiosity, knowledge and wisdom in me

Abstract

In electron Beam Welding, a beam of high energy electrons is accelerated through a high potential so that we can use its kinetic energy in the form of heat energy to join the materials. Electron Beam welding is used for welding both similar and dissimilar materials which is a big positive of this method. In this research, investigation has been carried out to study the mechanical properties of AISI 321 stainless steel joints by Electron Beam Welding. Orthogonal experiment was performed to study the special effects of different process parameters and weld type on the tensile strength of the joints, and the process parameters were optimized. Four different independent process variables were varied in the experiment and L9 (3^4) orthogonal array was made. Analysis of variance (ANOVA) was applied on these results to find out the effect of each independent variable and how much each variable is influencing the end results. Profile hardness was also carried to study the effect of welding on base material. The tensile strength, weld depth, weld width, heat affected zone and fusion was calculated for three different types of welds. Mold of Samples was prepared and was studied under high resolution microscope. Radiography of the welded samples was also carried out to verify the proper fusion, presence of cracks and porosity in the welded area. The thickness of SS 321 sheet used was 2mm. The optimum process parameters were calculated for electron beam welding.

Key Words: *Electron Beam Welding, ANOVA, Heat affected zone, Radiography*.

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CHAPTER 1: INTRODUCTION

1.1 Background

The requirement of new products having high strength to weight ratio in industries like automobiles, aerospace, nuclear, missile etc. have introduced new dimensions to material science. This has resulted in demanding condition to meet the current requirements of advanced materials which have to be developed but also, equally as important, the modern joining techniques to keep pace with the requirement of modern advancing technology. In modern era, various metal joining techniques are used which are conventional as well as non-conventional. The basic principle is to melt the metal by providing heat energy in various forms. This molten metal then solidifies to form the joint. The requirement of filler metal depends upon the type of welding as in some cases filler is sued while in modern metal joining techniques, we do not require any filler metal. The welding process is dependent upon the heat source and the efficiency of that source as it plays a decisive role in defining the weld geometry (shape and dimensions of weld bead). Welding process is linked with heat losses, which is minimum in electron beam welding as energy efficiency associated with this process is between 60 and 70 % [1]. Figure 1.1 depicts some of the relationship between different types of weld heat inputs when a butt joint is made. Here, electron beam welding having a high density heat input produces a narrow weld bead which is accompanied by minimum deformation caused in the work piece as compared to TIG, MIG and plasma welding, due to which post weld finishing can be reduced.

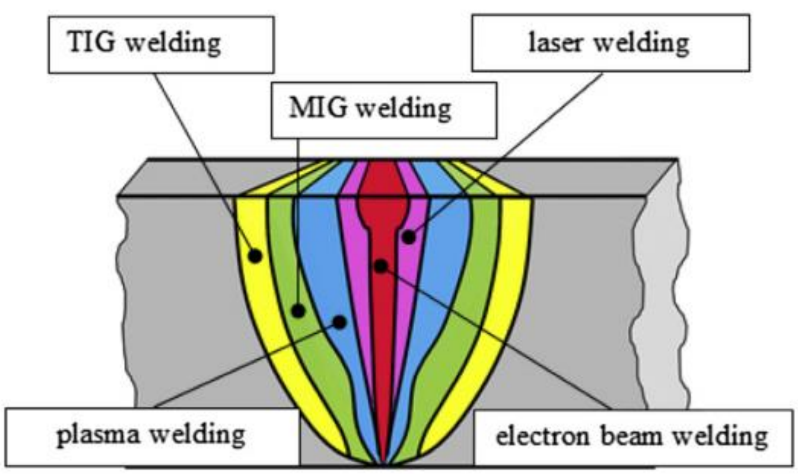

Figure 1.1: Relationship between heat input of different types of welding.

1.2 Types of Welding

There are various types of metal joining techniques.

1.2.1 Electric Arc Welding

In the earlier 19th century, the first arc welding process was developed and it became significant throughout the world as it was readily used in the ship making industry during the World War II. Now a days, it is used in joining of vehicles and steel readily. In this type of metal joining technique, heat energy is provided by the electric energy creating an electric arc between the electrodes (electrode can be consumable or non-consumable) and base metal which melts the metal and are joined in this way. The power supply can either be DC or AC depending upon use. The temperature during arc welding is very high due to which there is every possibility of oxygen from the atmosphere reacting with the base metal and produce oxide which is brittle in nature and is harmful for the weld strength. For this purpose, a protective slag or a shielding gas is used which reduces the direct contact of molten metal with air. This process can be performed manually, automatically or semi-automatically.

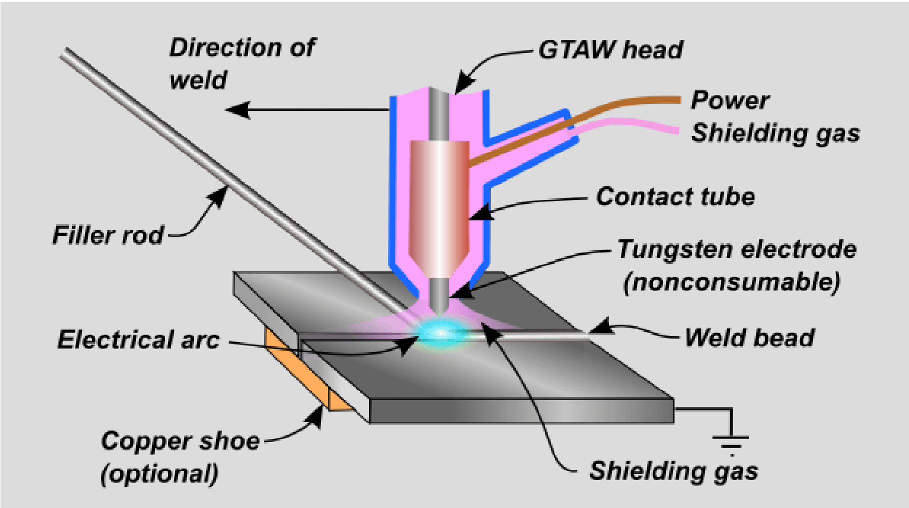

Figure 1.2: Electric arc welding

1.2.2 TIG Welding

Tungsten inert gas (TIG) welding also known as GTAW (Gas tungsten arc welding) is a type of arc welding which uses electrode made of tungsten to join the metals. The main attribute of this welding is that electrode used in welding process is non consumable. To protect the electrode and metal being joined from oxidation and to improve the quality of weld, an inert gas (Argon or helium) is used which shields the welding area from atmospheric contamination. A power supply providing a constant-current for welding provides electrical energy, which is conducted through the arc across a zone which is composed of ionized gas molecules and molten metal and vapors known as plasma.

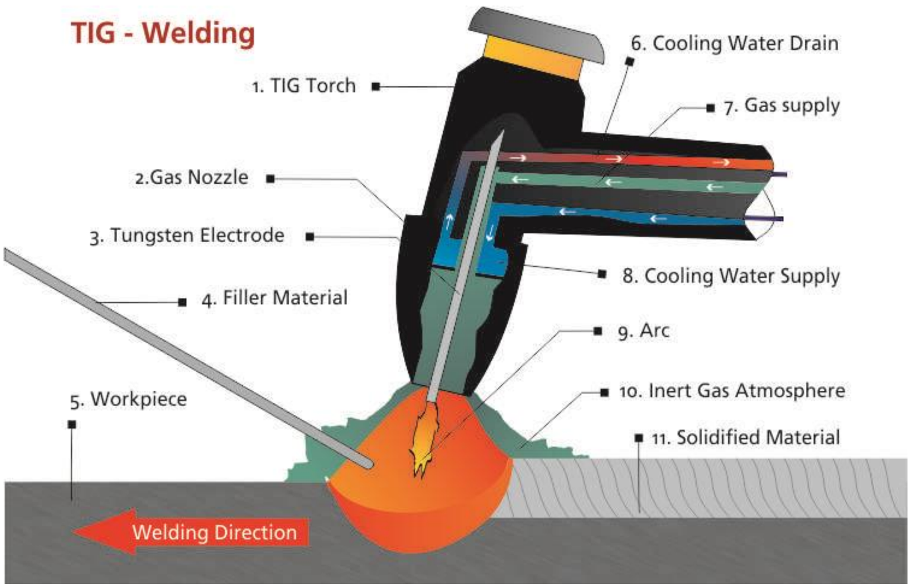

Figure 1.3: Tungsten Inert Gas welding

1.2.3 MIG Welding

Metal inert gas welding (also known as gas metal arc welding GMAW) is the type of welding which is equipped with continuous supply of solid wire electrode. An electric arc is produced between the electrode and the metal work piece, due to which heat is produced which in turn melts the metal and joining process (welding) takes place. The electrode used in MIG welding is consumed during the welding process and this is the main difference between GTAW and GMAW. The similarity between GTAW and GMAW is that in both processes, a shielding gas is used which protects or shields the weld from the atmospheric contamination and oxidation which can be detrimental to the weld strength. Initially, GMAW was used for the welding of aluminum. GMAW is an important welding process through which we can achieve high deposition rates and greater production.

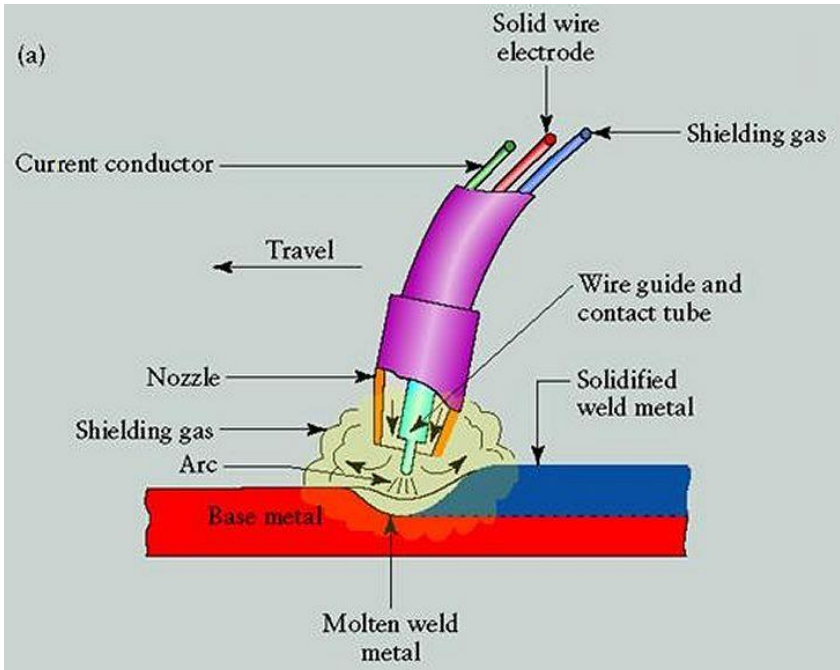

Figure 1.4: MIG welding

1.2.4 Laser Beam Welding

In conventional welding processes, a common problem existed known as "melting efficiency". Melting efficiency means that while welding of metals having high thermal conductivity, a large amount of heat was conducted away from the desired welded region at a very high rate. This resulted in low efficiency and high heat input. Melting efficiency is used to express the amount of heat actually used for welding process. In typical arc welding process, the melting efficiency falls below 50 %. However, in beam welding, this melting efficiency approaches 100 % as they use localized heating. Laser beam welding has attracted the eye of industry due to its promising results by producing welds of high quality and ultra-precision, reduced the distortion in metals being joined. In laser beam welding, an intense beam of high energy laser is directed on the work piece. It is basically a fusion welding process in which concentrated source of heat is produced by laser beam, which is focused on the work piece. The cavity between the two metals being joined has to be minimum as the diameter of a well-focused beam is very small. If we compare laser beam welding with arc welding, then the former is known by its high energy density, localized heating and ability to produce distortion free (with minimum distortion) joints. One of the main advantages of laser beam welding is that it can be performed in the absence of vacuum.

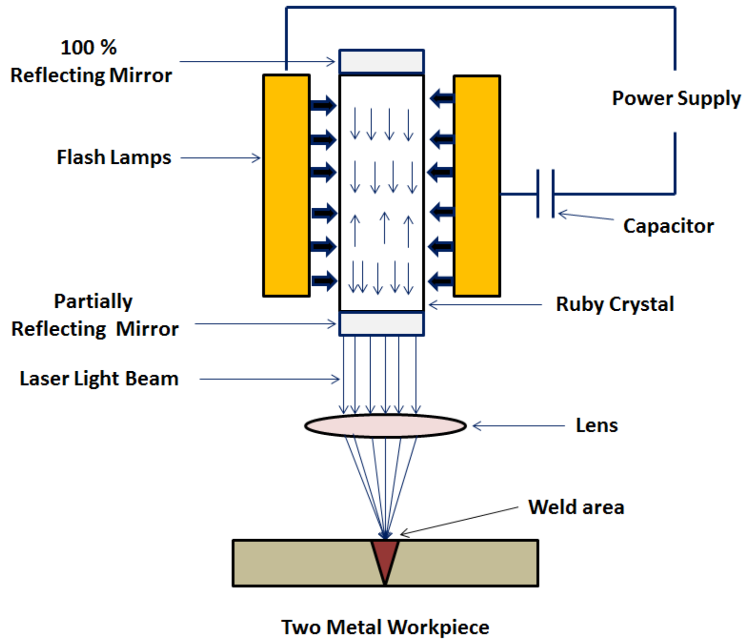

Figure 1.5: Laser Beam welding

1.3 Electron Beam Welding

Electron beam welding is a modern form of welding process which do not require any filler material.

1.3.1 History

The history of electron beam traces back to the discovery of electrons with experiments conducted by Hittorf and Crookes in an attempt to produce the cathode rays in 1869. The discovery of these fast moving rays known as cathode rays then led to the discovery of particular type of rays which were later named as electrons. Initially, at that time the heat which was produced due to the collision of electrons was considered very harmful as there was no process invented at that time to use this thermal power to the useful effect.

The first apparatus which was built to use this thermal effect for the useful purpose was by Marcelo Von Pirani. He melted tantalum powder using heat produced by electron beam. Later on, as the time progressed, this technique was also used for drilling purpose, oscillographs, and microscopes. The main issue aced at that time was of vacuum.

In the year 1952, a new era began in the history of physics when Dr. h.c. Karl-Heinz Steigerwald was able to build the first electron beam machine. He was looking to use these rays for the production of high power electron microscope. The experiments conducted by Dr. H.C. Karl-Heinz Steigerwald in which he used beam of electrons as source of thermal power for drilling watch stones and also for the soldering purpose, melting the metal and joining them under vacuum were very encouraging and this growth gathered speed at once.

After the discovery of electron beam processing machine in the year 1952, he was able to weld a 5 mm thick zircaloy and in the process he was able to find out that we can produce deep penetration welds with this technology. In the year 1963, he became the founder of the company named Steigerwald Strahltechnik GmbH, which manufactured high quality electron beam welding machines.

The use of electron beam welding has increased very rapidly worldwide after the invention of this technology. The use of this technology in the nuclear and defence production has increased its worth. It is also used in the field of medicine, aviation, automotive and railways etc.

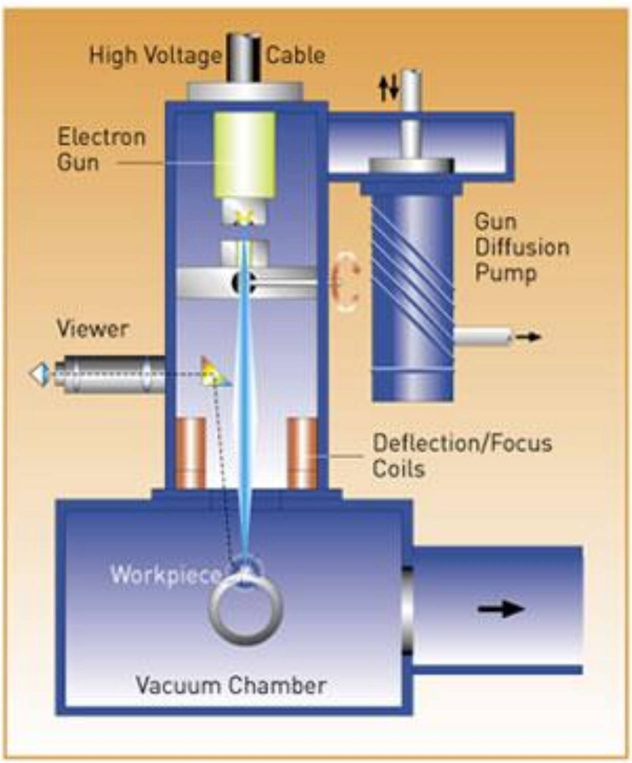

Figure 1.6: Electron Beam Welding Machine

1.3.2 Process

In electron beam welding, a very intense beam of electron is emitted from a cathode which is accelerated towards cathode by applying a very high potential. This beam is then focused using an electromagnetic lens on the work piece. The basic principle of electron beam welding is to convert the kinetic energy of high speed electrons into thermal energy which in turn is used to melt the metal.

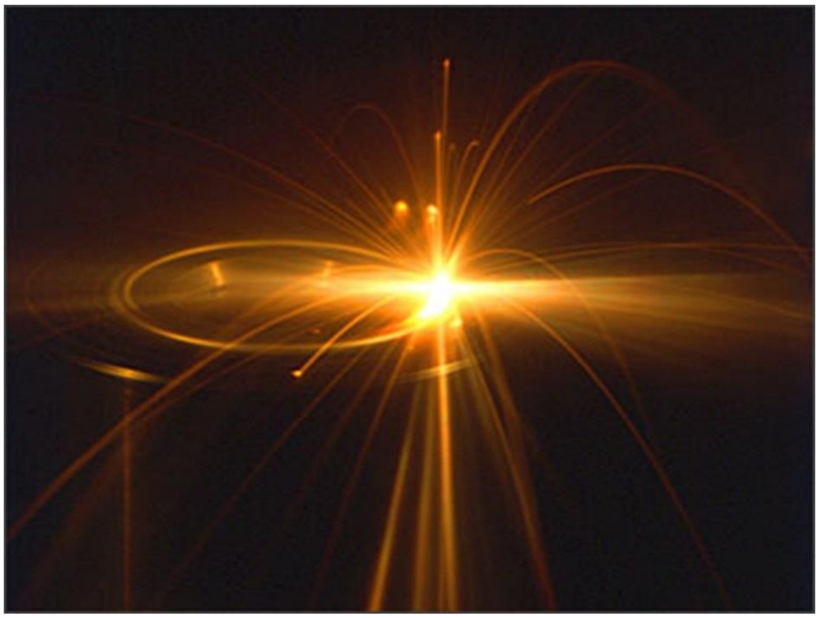

Figure 1.7: Electron Beam Welding

A comprehensive comparison between electron beam welding and other metal joining processes is presented in the table 1-1**.** [2]

Table 1-1: Comparison electron beam welding and arc welding of stainless steel having 150 mm thickness.

Parameter	Welding Process			
	Electron Beam Welding	Narrow gap GMAW	Narrow gap SAW	SAW
Current	0.27 A	260 A	650 A	510 A
Voltage	150 KV	30 V	30 V	28 V
Groove area	800mm^2	2100 mm^2	4900 mm^2	5900 mm^2
No of passes	1	35	81	143
Filler metal	0	23 Kg	54 Kg	66 Kg
Melting efficiency	7.7 Kg/h	5 Kg/h	13 Kg/h	9 Kg/h
Welding time	27 min	4h 35 min	4 h 11 min	7 h 27 min

1.3.2 Components of Electron Beam Welding Machine

A schematic diagram consisting of major components of electron beam welding machine is shown in figure 1.8.

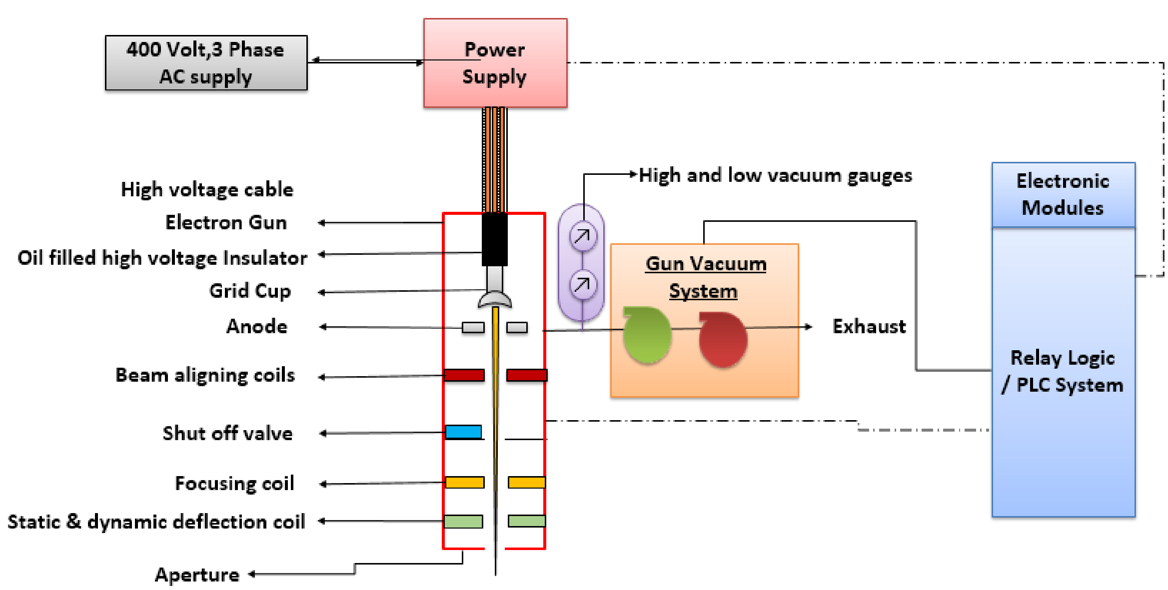

Figure 1.8: Electron Beam Welding Schematic diagram

In Modern era, variety of electron beam welding machine are available depending upon the use and requirement. These machines are categorized based upon their size, chamber dimensions, vacuum range, work piece diameter, linear displacement of work piece, angular speed, fixed or movable gun, non-vacuum or high vacuum, medium vacuum, beam deflection system etc. The major components of electron beam welding machine are [3]:

- Working chamber
- Manipulators
- Vacuum pumps
- Electron beam generator
- Gun pumping unit
- High voltage generator
- Grid power supply
- Filament power supply
- Controllers
- Cooling system to maintain temperature
- Pneumatic system

The modern Electron beam welding machines consist of a triode system for the generation and control of electron beam. A cathode which emits the electrons, cup which controls the flow and anode which accelerates the electrons. The source of electron in electron beam welding machine is a tungsten filament (cathode). This cathode is usually made of a tungsten alloy and is coated to increase its working life. Normally, the life of cathode is 20 working hours. With the passage of time and by emission of electrons the surface of cathode gets worn out and becomes brittle (Fig 1.8). Electric energy is provided to this filament due to which its temperature increases and results in thermal emission of electrons. So we have a sea of electrons at the tip of the filament which is ready to be bombarded to the work piece. It is important to control the flow of these electrons so that they do not move haphazardly inside the electron gun. A grid cup is used to control the flow of these electrons having a special shape to control the movement. The requirement of new products having high strength to weight ratio in industries like automobiles, aerospace, nuclear, missile etc. have introduced new dimensions to material science. This has resulted in demanding condition to meet the current requirements of advanced materials which have to be developed but also, equally as important, the modern joining techniques to keep pace with the requirement of modern advancing technology. In modern era, various metal joining techniques are used which are conventional as well as non-conventional. The basic principle is to melt the metal by providing heat energy in various forms. This molten metal then solidifies to form the joint. The requirement of filler metal depends upon the type of welding as in some cases filler is used while modern metal joining techniques do not require any filler metal. The welding process is dependent upon the heat source and the efficiency of that source as it plays a decisive role in defining the weld geometry (shape and dimensions of weld bead).

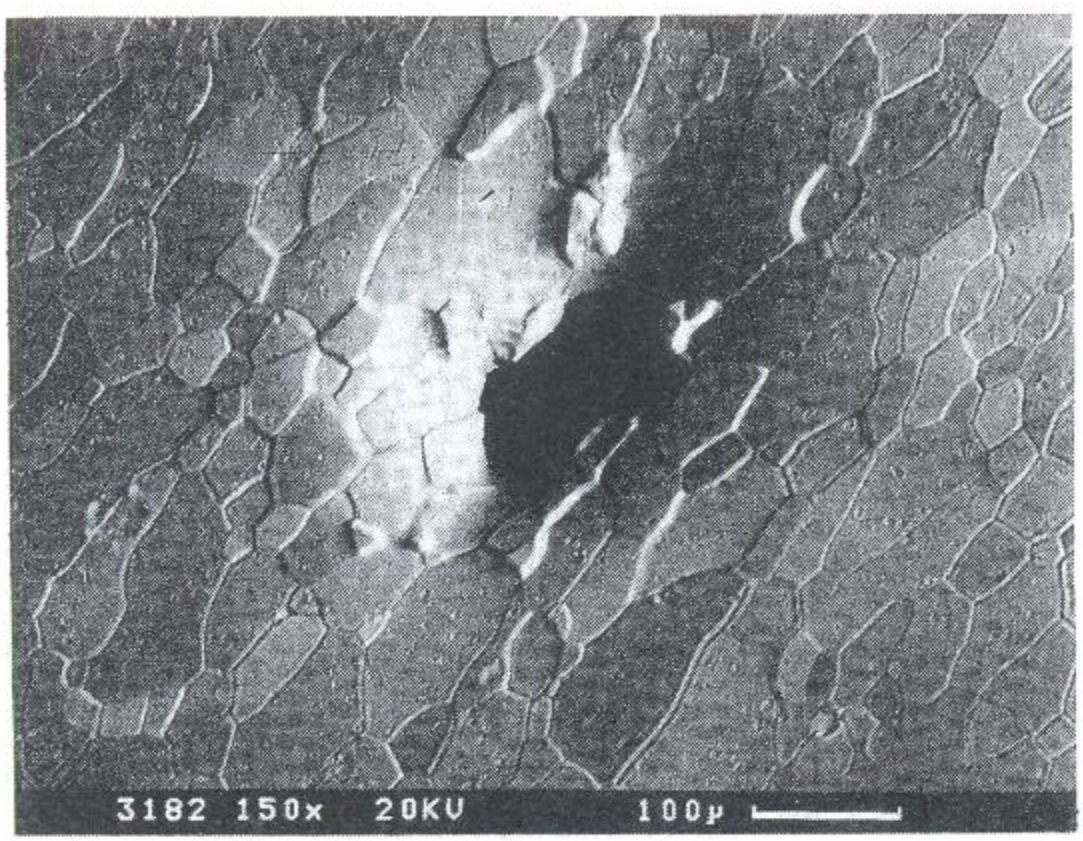

Figure.1.9: Emission surface of strip cathode torn by ion bombardment

The welding process usually takes place in vacuum, for this purpose a vacuum chamber is there having very high vacuum. The work piece is placed inside this chamber. A control unit is placed outside the chamber which is used to regulate the beam current and high voltage.

1.3.3 Principle of Electron Beam Welding

Electron is a very light particle and its mass is 9 X 10^{-31} Kg and it is 1836 times lighter than proton. The most important thing is that it carries an electric charge, having magnitude of 1.6 X 10^{-19}. This feature of having a charge makes it important because it makes possible to accelerate the electrons at such a high speed that they attain enough kinetic energy which is used melt the metals. Electric charge also makes it possible to deflect the electron using an electric or magnetic field to produce the desired the results. In a typical electron beam welding machine in which welding is done under a high vacuum and has high voltage 150 KV, the electrons reach a speed up to 2 X 10^{8} m/s, or in other words we can say that electrons reach a speed up to two third speed of light which imparts high kinetic energy to these electrons. These electrons strike the work piece with high velocity and give up their kinetic energy [4]. The relationship between accelerating voltage and speed of electrons is given in figure.1.8

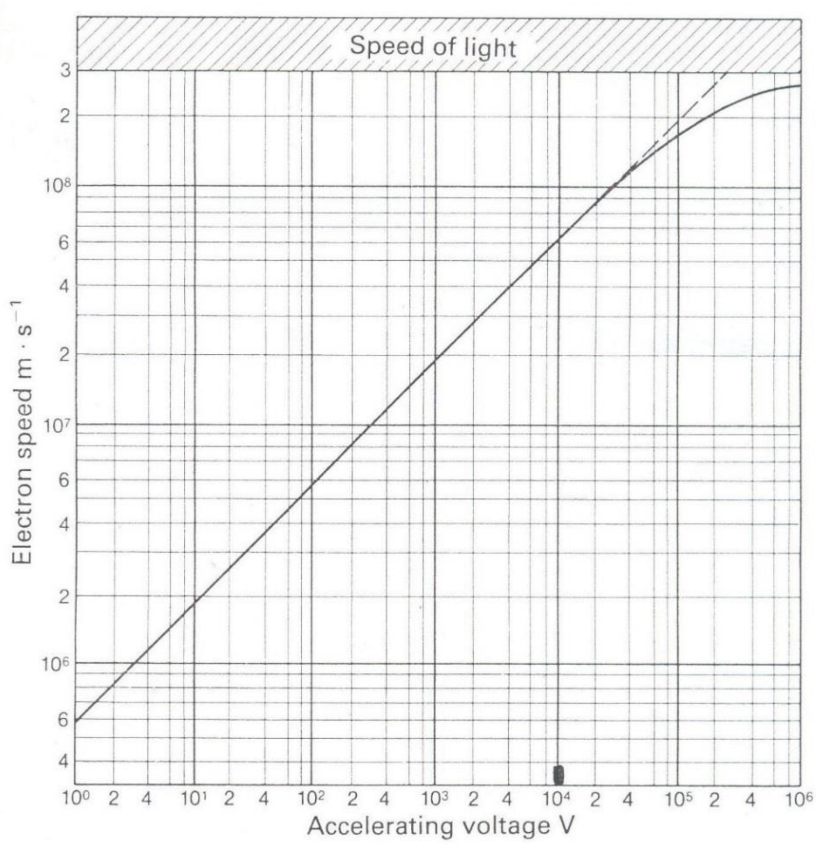

Figure.1.10: Relationship between accelerating voltage and speed of electrons.

From classical point of view, the collision of these high speed electrons cannot transfer their energy directly to the lattice atoms having mass M, rather this energy is first transferred to the outer electrons having mass m, the ratio K of the electron energy transferred to lattice electrons and energy prion to collision is given by [5].

$$K = \frac{2Mm}{(M+m)^2}$$

When electron beam is bombarded on the work piece, it interacts with the electrons and the atoms of that element due to which following emissions take place [6].

- Back scattered electrons
- Secondary electrons
- Auger electrons
- X-Rays
- Fluorescence
- Radiations due to heat

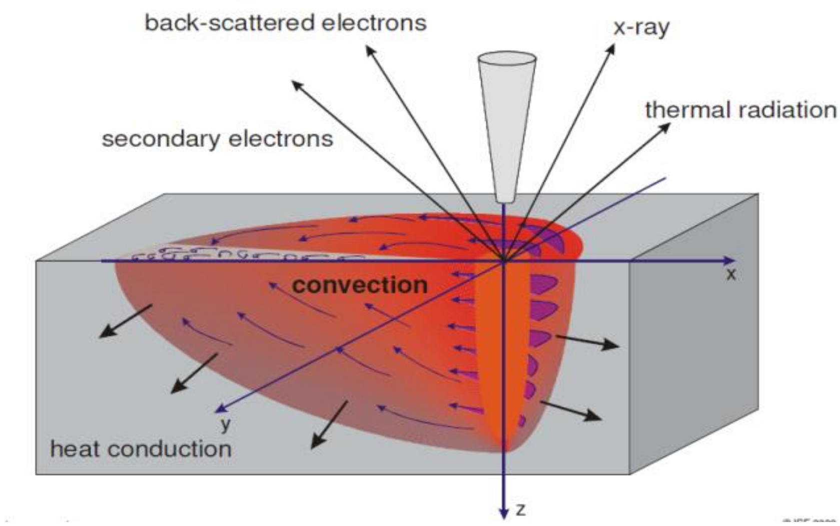

Figure.1.11 Electron beam interaction with lattice electrons

A very high temperature can be attained with electron beam welding because the lattice electrons transmit the vibrational energy to the total lattice which results in high amplitude of vibration which in turn increases the temperature of work piece. The temperature is increased to such a level that the melting point is reached and material starts melting and even evaporates which allows the beam to penetrate deep into the work piece and carry out deep welds. The extent to which a beam penetrates into a work piece depends upon the power density of beam, the total power applied to the beam and also the work piece (elements, thermal conductivity etc.) When a high power electron beam is penetrated into a metal piece, plasma is produced due to ionization and evaporation of the elements present in the metal takes place due to which the positive ions produced and electrons are used for focusing purpose in order to maintain high electron density in the beam.

1.3.4 Heat Input from Electron Beam

We can calculate the heat output produced by an electron beam.

1electron volt = 1.6×10^{-12} erg,

1 erg = 2.39×10^{-8} Cal,

1 electron volt = $1.6 \times 10^{-12} \times 2.39 \times 10^{-8}$,

1 electron volt = 3.7×10^{-29} cal.

When accelerating voltage is 150,000 V or 150 KV, energy of each electron

$3.7 \times 10^{-20} \times 1.5 \times 10^{5}$

5.56×10^{-15} Cal,

1 A 6.28×10^{18} electrons/sec,

0.01 A = 6.28×10^{16} electrons/sec,

Beam energy = $6.28 \times 10^{16} \times 5.56 \times 10^{-15}$

=349 Cal/sec.

So, if we have a beam of 0.01A accelerated through a potential difference of 150 KV, it carries 349 Cal/sec of energy. [7]

1.3.5 Keyhole Formation

The power density of electron beam is very high. The beam having density higher than 10^5 W/cm^2 transmit their energy to the work piece so rapidly that the metal melts even before it can transfer the energy by conduction and even evaporates when heated further and turns into super-heated vapor. At high temperature, the vapor expands and moves in upward direction due to which the molten envelope in pushed downwards. A depression is formed which allows the fresh electrons to strike metal deep and forms a keyhole is formed having superheated vapor in the center and molten envelope in the surrounding.

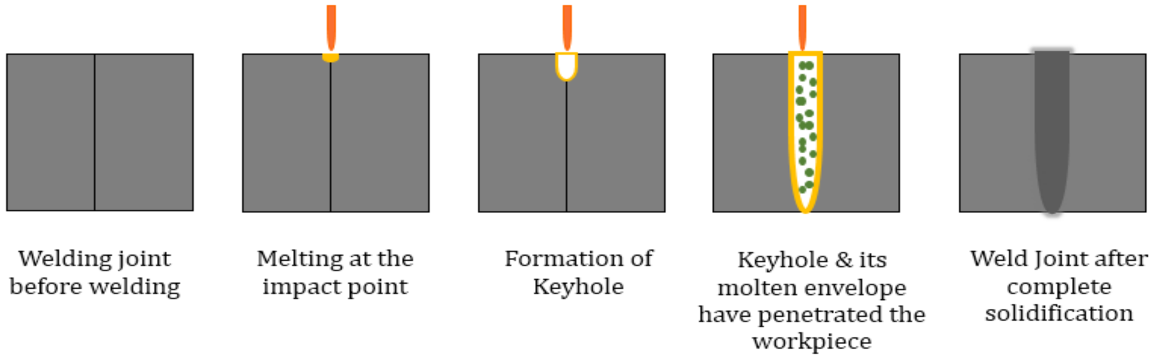

Figure.1.12: Formation of keyhole

Due to formation of this keyhole, electron beam welding can penetrate through the work piece even if the piece is several centimeters thick. For the formation of the keyhole and to keep the keyhole open to permit the transfer of energy required for welding process, various forces must interact. It is due to this feature that we can weld from 0.01 mm to 250 mm thick steel plates and up to 500 mm of aluminum [8]. These forces are shown in figure 1.11.

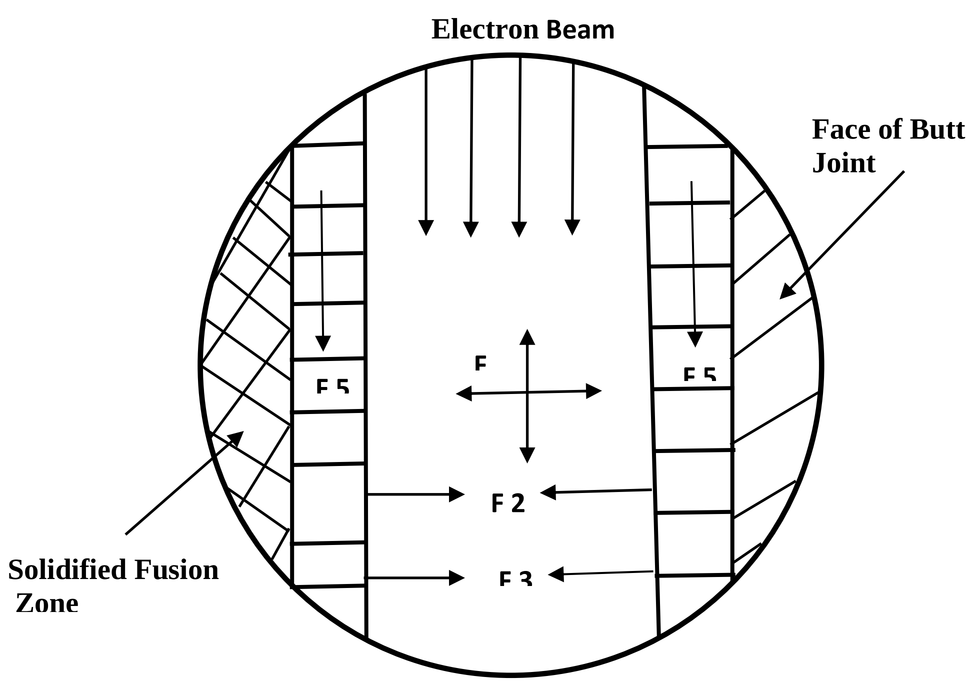

Figure 1.13 The major forces present in the keyhole for deep penetration of electron beam

F1 = Vapor Pressure

F2 = Force resulting from surface tension

F3 = Hydrostatic pressure

F4 = Frictional Force

F5 = Weight of the molten metal

1.3.6 Energy Generated by Electron Beam

In order to calculate the beam energy, we make use of the following equation.

$$P = I \times V \qquad (1)$$

If we take the beam current to be 5 mA and use accelerating voltage 100 KV, then

I = Beam current = 5 mA or 5×10^{-3} A

V = Accelerating voltage = 100 KV = 100×10^{3} V

Putting these values into equation (1)

$$P = 5 \times 10^{-3} \times 100 \times 10^{3}$$

P = 500 Watt (J/sec)

To calculate the energy, we use the value of welding time. If welding time is 10 sec, then energy generated will be

E_G = P x Welding time

Welding time = 10 sec

$E_G = 500 \times 10$

E_G = 5000 J or 5 KJ

So, at 100KV, 5mA and 10s welding time, the electron beam generates 5 KJ of energy.

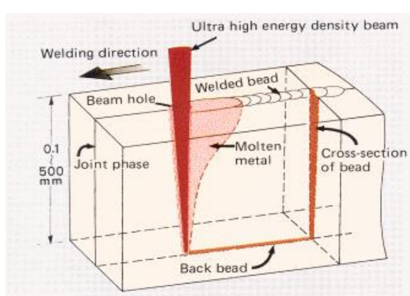

Figure 1.14: Energy transferred by EBW

1.3.7 Energy transferred to work piece (ET)

To calculate the energy transferred to the workpiece, we make use of following equation:

Efficiency = $\{(E_T) / (E_G)\}$ x100

E_T = Energy transferred to work piece

E_G = Energy generated by the source

For EBW, efficiency = 80-95 %

Taking efficiency= 80%

80= $(E_T/5)$ x 100

E_T = 4 KJ

Energy transferred to work piece during welding = 4 KJ

1.3.8 Energy required for melting of unit volume (Um)

Um= K x Tm^2

Um= Energy required to melt unit volume (J/mm^3)

K is constant = 3.33×10^{-6} for Kelvin scale

Tm = Melting point of material

(For steel Tm= 1435°C or 1708 K)

Um= $3.33 \times 10^{-6} \times 1708^2$

Um= 9.71 J/mm^3

9.71 J of energy is required to melt unit volume of Steel.

1.3.9 Advantages of electron beam welding

- Deep penetration welding
- High depth to width ratio
- High welding speed
- Low distortion

- No filler or additional material
- No post weld cleaning
- Weight saving
- Welding of dissimilar material
- No oxidation of welded joint.
- Variable working distance.
- No edge preparation.
- High power density
- Inertia free oscillation of electron beam
- Computer monitoring

1.3.10 Disadvantage of electron beam welding

- Difference of melting point in dissimilar metals
- Vacuum environment
- High cost
- High accuracy for jobs preparation
- Brittleness due to rapid solidification
- High vacuum time for large chambers
- High maintenance cost

Chapter 2: Literature Review

Electron beam welding is a useful and multipurpose metal joining technology. We can weld different grades of steel with the help of this technique. Even refractory metals such as molybdenum, tungsten and niobium, which are very difficult to weld by conventional welding techniques can be welded by electron beam welding. Dissimilar metals have also been joined using electron beam welding. Even with such a versatile welding technique, every metal cannot be joined and there is a limitation which is due to difference in chemical composition, coefficient of thermal expansion, thermal conductivity, solidification properties etc. [8]. To find out which material can be welded with one another, Figure 2 gives the possible combinations of materials [9]. Electron beam welding is characterized by high power density and a very efficient welding process as most of the heat input is used for welding purpose. Due to rapid solidification and fast rate of cooling (10^5 Ks^{-1}) associated with electron beam welding, convex reinforcement is observed. This reinforcement also occurs due to alteration in density of base material and the molten weld pool. Normally single pass weld is used for welding process, but it has a drawback of uneven and undue reinforcement having detrimental effect to the weld. Lack of fusion and porosity in weld zone is also observed due to these factors. These issues can be resolved if multiple pass weld is performed and weld quality is improved [10].

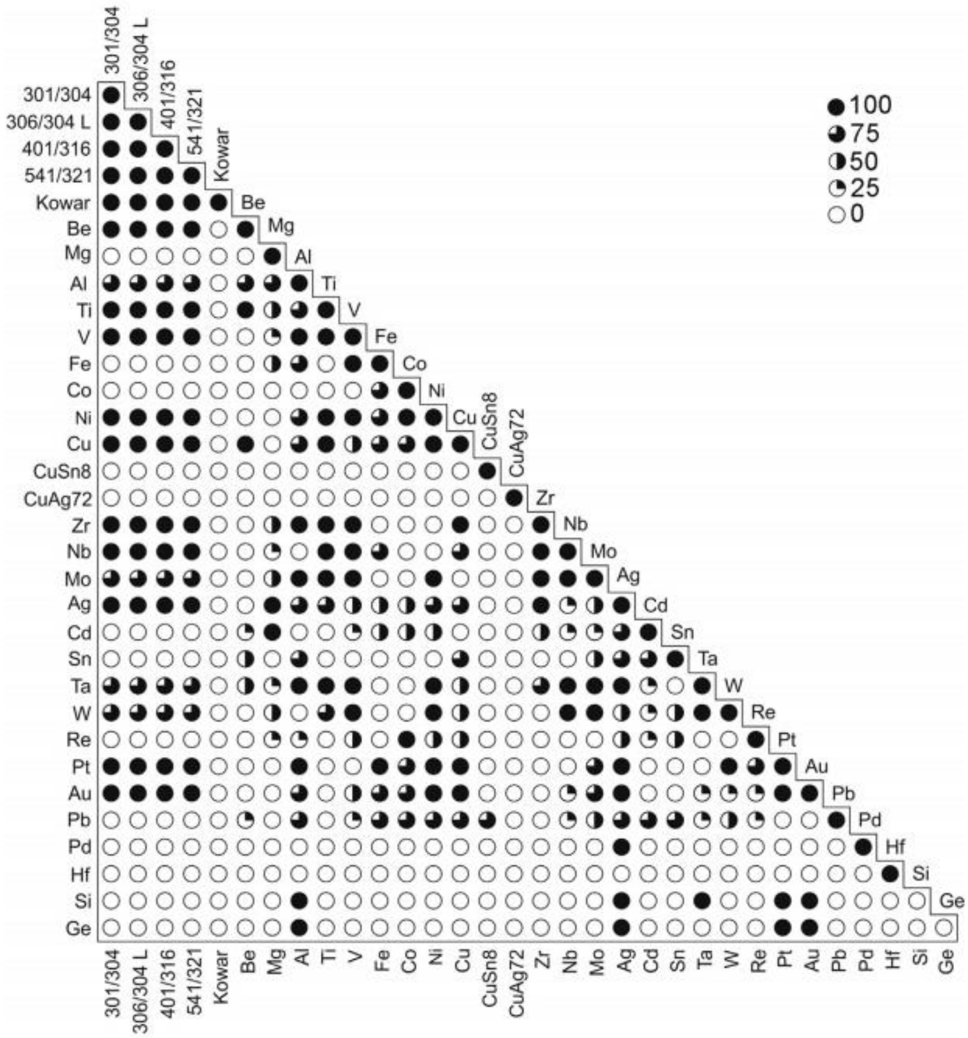

Figure 2.1: Weldability of materials by using EBW

2.1 Effect of Accelerating Voltage

In recent research, the accelerating voltage has been proved to be a major factor in intensification of kinetic energy [11], it also effects depth of welding directly [12]. By increasing the accelerating voltage, the beam focus is also affected and if beam is properly focused, the spot diameter is reduced impinging the beam on work piece with greater intensity [13]. It is also verified that by increasing the accelerating voltage of electron beam welding machine, emission of electron from tungsten filament is also enhanced which results in reliability and steadiness of beam [14].The effect of increasing the accelerating voltage on melt pool and melt volume is also studied and found that there is a direct relation between accelerating voltage and melt volume [15]. The increase in kinetic energy of electron beam is also observed which also causes upsurge in the melt volume. One of the few limitations of electron beam welding is it cannot weld magnetic materials, as electron being a charged particle is deflected in magnetic field and hence we cannot focus the electron on the work piece even by increasing the beam power or accelerating voltage [16]. The heat produced in electron beam welding is localized if the beam is well focused on the work piece which is the main strength of EB welding as the increased voltage imparts high kinetic energy to the charged electrons, but the drawback associated with it is closes tolerances have to be maintained during machining for EB joints as even 0.1 mm gap is very high and cannot be accepted for welding. [16]

2.2 Effect of Welding Speed

The welding speed is an important parameter in electron beam welding and plays vital role in strength of joint. Different speeds have different effects on weld geometry and shape of weld. The welding speed can be varied both in linear welds as well as circular welds. Welding speed affects the joint formation and the heat affected zone. If the welding speed is decreased, there is an increase in heat affected zone as the heat input is increased ($Q=VI/S$, where Q is heat input, V is accelerating voltage, I is beam current and S is speed) and also the melt volume is increased which results in increase in fusion zone and also the grain size is increased [17]. The shape of weld also changes as we play with the welding speed. The weld width is inversely proportional to the welding speed i.e. if we decrease the welding speed, weld width is increased as the heat input is amplified and vice versa [17]. In this way we can achieve grain refining by optimizing the weld speed. Fatigue properties of joint is also improved by optimizing the weld speed (29% increase was observed) [17]. If the welding speed is kept high, little distortion takes place in the work piece and it also reduces the heat affected zone [18]. Electron beam welding has the quality of reproducing the results by repeating the test runs number of times. If welding is carried at the same parameters and there is no change in accelerating voltage, beam current, weld speed, focal distance, joint type, material etc. then we can have same results by repeating the weld number of times, also electron beam welding machines having power of more than 60 KV produce X-Rays due to inner shell transition. For this purpose, these machines are lead cladded (both gun and chamber) to prevent the emission of X-Rays and to protect workers from direct exposure to these harmful X-Rays [18].

2.3 Focusing

Electron beam is emitted from tungsten cathode and is accelerated towards the work piece by the application of high accelerating voltage. This beam after passing through annular anode moves towards the work piece. If we strike the beam on work piece in this condition, the electrons will be scattered and their energy will not be confined at a single spot. Hence it cannot be used to melt the material and welding process cannot be achieved. To overcome this problem, an electromagnetic lens (focus lens) is used which converges the beam and points it at the work piece. Siddaiah [19] et. al studied the effect of focusing on weld profile of AISI 304 and found that the weld profile is deeply affected by change in focusing current and hence the focus point. The weld geometry which includes the weld depth, width, beam width and heat affected zone depends directly upon the focusing current. To achieve high quality weld, focusing plays an important role. To achieve a deep and high quality weld, weld speed and focusing are very important [20]. Effect of change in focus current can be illustrated in Fig. 2.2.

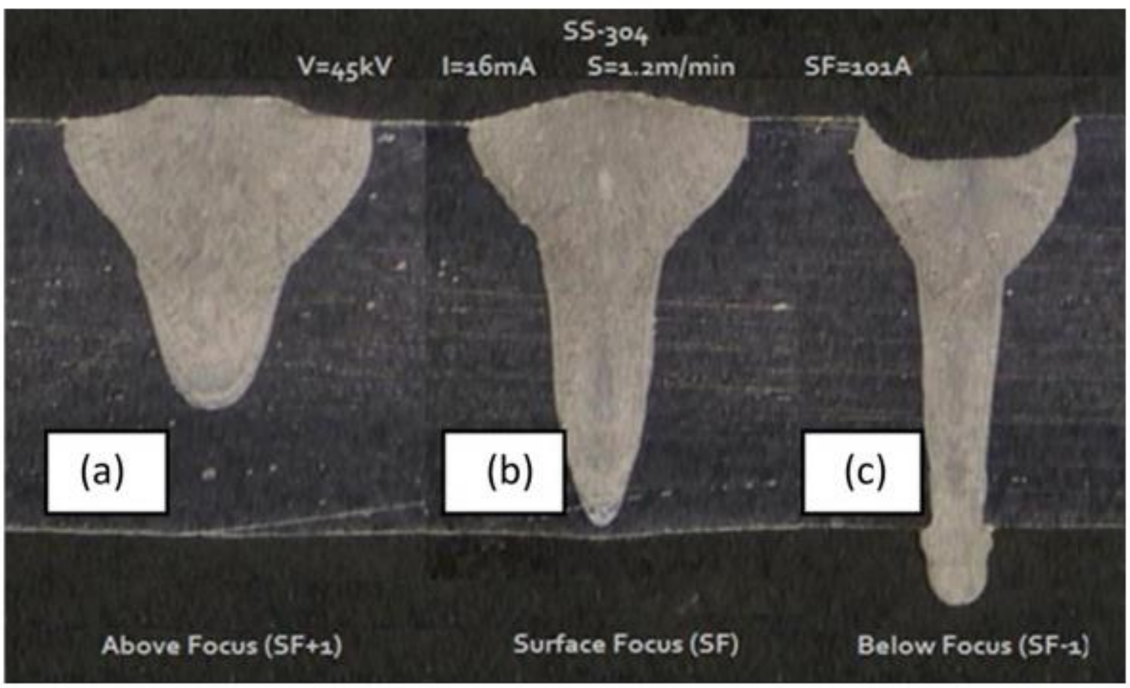

Figure 2.2: Effect of change in focus current

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2.4 Standardization

In modern metal joining techniques, the processes which are not direct under manual control like electron beam welding, there is a requirement to establish certain machine parameters and operator manuals as well as qualification standards which covers variety of issues related to electron beam welding. ISO standard 14744 [21, - 26] is based on welding parameters, inspection and weld qualification. The standard ensures that electron beam weld produced are of high quality. The results are consistent and repeatable during the same operating conditions. The standards take care of machine parameters including high voltage, beam current generation, value and uniformity of beam current, speed of welding and electromagnetic lens current used to focus the beam and specify the deviation in their values both for short term operations as well as long term use. Accuracies regarding run-out of the job is also addressed in these standards. The ISO 13919 is the standard which covers the levels of imperfections in electron beam welded joints made by stainless steel. The selection of standard should be based upon the design considerations and end requirement of the object. The basic requirements and guidelines for EB welding are given in EN ISO15609 standard [27].

The weld produced by electron beam welding technology can be qualified by using the some basic principles which are given as follows:

1. Based on previous welding experience [28]
2. Following an internationally accepted welding procedure [29]
3. Using results achieved from pre-production trials [30]
4. Adopting welding procedure test [31]

Another factor which plays a vital role in EB welding is the skill level of operator and is valued worldwide and their level of competence and minimum requirements are described in international standard ISO 14732 [32]. Both the international standards as well as recommendations made based upon experience are very important and useful in development of electron beam welding technology. The famous welding society across the world is American Welding Society (AWS) [33] and another well recognized is Deutscher Verband- German Welding Society [34]. A few standards in the field of electron beam welding process are given in the table 2-1.

Table 2-1: Standards of Electron Beam Welding Process

S.No	Standard	Title	Scope
1	ISO 14744	Welding. Acceptance inspection of electron beam welding machines	Specifies requirements for acceptance inspection of electron beam welding machines 2 EN 1011-7 Welding. Recommendations for welding of metallic materials Part 7: Electron beam welding
2	EN 10117	Welding. Recommendations for welding of metallic materials Part 7: Electron beam welding	Details on quality requirements, production welding facilities as well as the weldability of some materials
3	EN ISO3834	Quality requirements for fusion welding of metallic materials	Defines comprehensive quality requirements for fusion welding of metallic materials both in workshops and at field installation sites
4	ISO 13919	Welding. Electron and laser beam welded joints. Guidance on quality levels for imperfections	Gives guidance on quality levels of imperfections in electron and laser beam welded joints in steel. Three levels are given which refer to production quality
5	ISO 15609-3	Specification and qualification of welding procedures for metallic materials. Welding procedure specification. Part 3: Electron beam welding	Specifies requirements for the content of welding procedure specifications for electron beam welding
6	ISO 15607	Specification and qualification of welding procedures for metallic materials. General rules	Defines general rules for the specification and qualification of welding procedures for metallic materials
7	ISO 15611	Specification and qualification of welding procedures for metallic materials. Qualification based on previous welding experience	Gives the necessary information to explain the requirements referenced in ISO 15607 concerning the qualification of welding procedures based on previous welding experience

In past, work has been done on American Iron and Steel Institute (AISI) 304 plates by welding them using butt-weld and was compared by studying genetic algorithm neural network (GANN) and back propagation neural network (BPNN) techniques and using them to optimize the weld profile (weld width, weld depth and bead width) and ultimate tensile strength [35]. Taguchi design has not been used to optimize the parameters of electron beam welding and heat affected zone calculation along with micro hardness profile generation of the weld zone are the areas which have not been focused yet.

2.5 Temperature distribution and welding defects

The temperature during welding reaches very high and material is melted to produce the joint. The efficiency of the joint produced by EB is very high. Yanhong Tian et al. studied the effect of current and speed on weld geometry and defects produced during welding. He found that if we increase the current during welding, the distortion in the material also increases, however the same is opposite in case of welding speed. He also modeled the temperature of the weld cavity and observed the maximum temperature at the bottom of the weld cavity [36]. Chengcai Lui et al also studied the effect of current on welding structure. It was found through numerical simulations and by using double ellipsoid heat source that the temperature inside keyhole is very high but it is below the boiling point of material. The increase in welding current results in enlargement of beam width and also the depth of penetration. The defects including internal stresses produced during welding can be minimized by high welding speed [37]. Temperature distribution inside the weld zone and in surrounding area is very important as it decides the value of heat affected zone which in turn is responsible of weld strength. This also has an effect on the thermal stress which is induced in the joint during welding process. Zhang et. al studied the temperature and heating rate during electron beam welding of stainless steel 304 with titanium alloy. It was concluded that the heating rate at a distance of about 2-3 mm from the weld center is approximately 1000 °C/sec and the longitudinal thermal stress inside the material is converted from compressive to tensile stress as the welding process is performed [38].

2.6 Applications

Electron beam welding technology is advanced form of welding and is useful in various industries [39, 40, 41, 42]:

- ❖ Automotive Industry

  In automotive industry, the transmission system, specially gear assembly, the housing of engine, air bags, cam shafts and crank shafts, turbo-compressors and catalysts etc. are welded using electron beam welding technology

- ❖ Aviation Industry

  Titanium is an important metal and is used in defense projects worldwide due to its high strength. The titanium tanks are also welded using electron beam welding to be used in rockets and satellites. In these tanks, high pressure propylene gas is filled. Aluminum is widely used in aviation due to its light weight. The aluminum containers are welded using electron beam welding for efficient and high strength welds. Turbine blades along with its housing, fuselage, perforated bottoms in rockets are uses in aviation industry.

- ❖ Power engineering and electrical power engineering

  Welding of high current flexible connectors and containers used for collecting nuclear waste are welded using EB welding

- ❖ Mechanical Engineering

  Applications in marine engineering (welding of transport hooks), hydraulic cylinders, sensors of temperature and deformations, catalyst for continuous casting of steel etc.

- ❖ Medical

  Toothed gear element are welded using electron beam welding used in artificial limbs, applications in quick prototyping of endoprosthesis elements and impart surface processing are few examples of importance of electron beam welding in medical field.

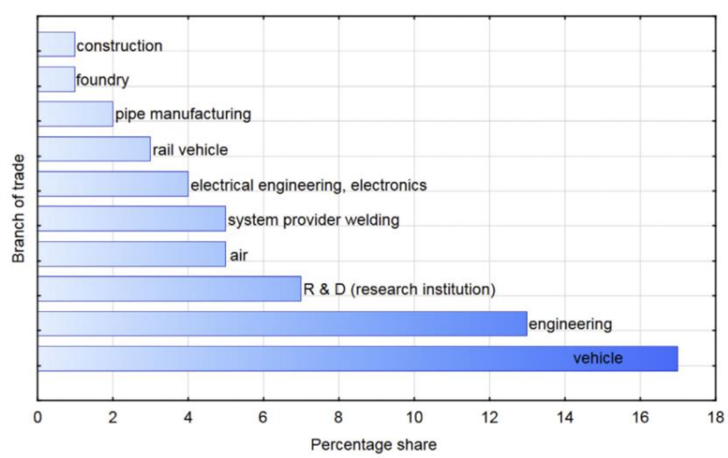


Figure 2.3: Electron Beam Welding Applications

Chapter 3 Methodology

The machine used for electron beam welding was of 100 KV and 50 mA (5 KW power). The welding process was conducted under vacuum. The vacuum of gun was in the range of 10^{-5} mbar, while the chamber vacuum was in range of 10^{-4} mbar. Range of welding speeds were available both in linear as well as rotary. The work piece was placed in working chamber and the chamber was evacuated using vacuum pumps. After reaching the desired level of vacuum, beam was turned on and dropped on the work piece. After that, the focusing of beam was adjusted by varying the current of electromagnetic lens (focusing current) using a potentiometer. Optical viewing system was used to observe the beam spot diameter. After varying the focusing current on work piece, the best focus was established and the value of focusing current was recorded. This value was to be used in actual experiment to achieve the best possible results. The test piece which was used for tuning the focus was then discarded and new samples were used for experimental purpose.

3.1 Selection of material

Metal which has been selected for the analysis is American Iron and Steen Institution (AISI) 321. A rolled sheet of stainless steel 321 having thickness of 2 mm is used. The base material prior to welding is shown in figure 3.1

Figure 3.1: Samples before welding

3.2 Preparation of Samples

A rolled sheet of American Iron and Steen Institution (AISI) 321 was procured from the market in order to prepare the samples. The thickness of sheet was 2 mm. The sheet was then cut into square shape of 70 mm X 70 mm using a CNC hydraulic shearing machine. The CNC hydraulic press is shown in the figure 3.2.

Figure 3.2: CNC hydraulic Press

The picture of samples cut from shearing machine is given below:

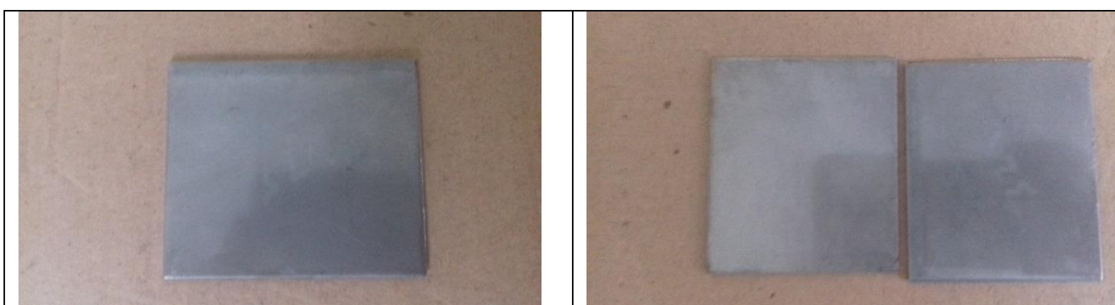


Figure 3.3: Samples after cutting

As the sheet was cut using shearing machine, there was burr formation at the edges of the sheet cut. For electron beam welding, the joint has to be flush without any burr or irregularity, so this has to be taken care of. This edge was then grinded using a surface grinding machine so that every edge was at 90° to each other. These edges were then lapped using lapping pastes of fine quality to polish the surfaces.

3.3 Design of Experiment

The parameters which were chosen to be optimized were beam current, accelerating voltage, welding speed and the type of joint. Three different types of joints were to be welded using electron beam welding technique. The joint types chosen were:

I. Butt Joint
II. Lap Joint
III. Scarf Joint

If we calculate the number of combinations which can be made of these four parameter or variables, we get the figure of 81. This means that we have to conduct 81 experiments, and at least two runs of each combination by which we have 162 experiments. So we had to run 162 experiments to find out the effect of each parameter and achieve the optimum parameters. However, if we use Taguchi's design of experiment, then an orthogonal array of L9 of L27 can be made. Here L9 was selected with repetition of 2 runs to get the optimum results. Process parameters and level details are given in table 3-1.

Table 3-1: Welding Parameters for Design of Experiment

S. No	**Voltage (KV)**	**Current (mA)**	**Speed (mm/s)**	**Joint Type**
1	80	8	10	Butt
2	80	9	20	Lap
3	80	10	30	Scarf
4	90	8	20	Scarf
5	90	9	30	Butt

6	90	10	10	Lap
7	100	8	30	Lap
8	100	9	10	Scarf
9	100	10	20	Butt

3.4 Preparation of joint type

Samples of butt joint were already prepared as there was no extra machining required after lapping process. For lap joint, a 1 mm deep and 2 mm in length cut was made using milling machine. In this way a male and female part were created for lap joint. One sample was seated on the other with the help of 2 mm step to create lap joint. This was done to keep the axis of joint in the same plane so that when the samples are used for ultimate tensile stress calculation, the axis of applied force remains the same and does not affect the results.

The third type of joint used was scarf joint. This joint was prepared using angular milling. A 2 mm cut at an angle of 45° was made at the desired edge. This edge was again lapped using lapping paste to remove any burr incorporated during milling process. Three pairs were then selected by matching their lapped edges for the best combination. The sample prepared are shown in Fig. 3.4.

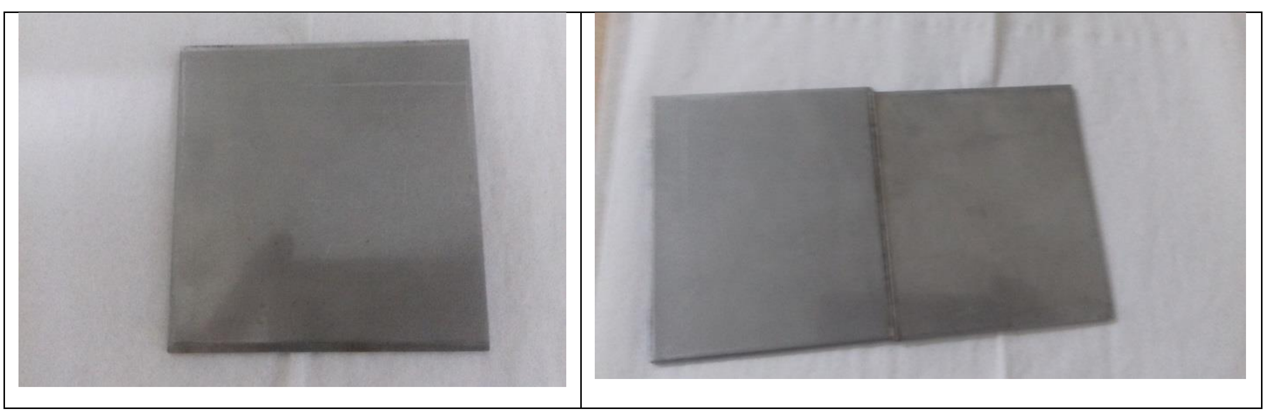


Figure: 3.4: Samples prepared for welding

3.5 Chemical Composition

The composition of the samples was also calculated to find out the exact percentage of alloying elements. For this purpose, scanning electron microscope was used. The samples are first cleaned using acetone so that any impurity on the surface is not included in the results.

3.6 Mechanical Testing

The welded samples are subjected to mechanical testing to find out the strength of EB welded joint. There are two types of tests conducted to find the strength and efficiency of welded joints.

1. Nondestructive testing
2. Destructive testing

3.6.1 Nondestructive Testing

Nondestructive testing in an evaluation technique used on engineering materials to find out their usefulness without physically damaging the material. Mostly nondestructive techniques emphasize on highlighting the defects including cracks (surface and internal cracks). Nondestructive testing can be used for analysis of failure and also to avoid any future failures. The major techniques followed in Nondestructive testing include ultrasonic testing and X-radiography. In my research, I will use X-radiography to check the fusion in the weld zone and also the porosity.

X-radiography

X-radiography is similar to the medical X-ray which is used to get the image of the body parts (mostly bones) and find out about any defect. Similarly, we use x-radiography to get the image of area of interest (weld zone in our case).

For any material, in order to calculate the intensity of beam I, which is transmitted through the thickness (x) of material can be found using Beer's law:

$$I = I_o e^{-\mu x}$$

Where I_o is the energy of beam incident and linear absorption co-efficient of given material is represented by μ. The intensity is related to the number of photons. Linear absorption co-efficient of various elements are given in the table 3-2 [44].

Table 3-2: Linear absorption co-efficient of elements for an X-Ray 100 KeV (0.1 MeV)

S.No	Element Name	Symbol	Atomic Number	μ (mm^{-1})
1	Aluminum	Al	13	0.0459
2	Titanium	Ti	22	0.124
3	Iron	Fe	26	0.293
4	Nickel	Ni	28	0.396
5	Copper	Cu	29	0.410
6	Zinc	Zn	30	0.3556
7	Tungsten	W	74	8.15
8	Lead	Pb	82	6.2

The samples were subjected to radiography to radiography to check for any cracks underlying the weld surface as it can be detrimental to the joint strength.

3.6.2 Destructive Testing

In destructive testing, the analysis of material is done at the cost of its shape and physical appearance. The common example of destructive testing in ultimate tensile strength calculation in which the sample is applied tensile load till the point its maximum strength is reached and the specimen breaks. Similarly, for carrying out EDS analysis, destructive test has to be done to find out the chemical composition. I used EDS to find out the composition of parent material. The strength was calculated using tensile testing machine. The machine is shown in the Fig. 3.5.

Figure 3.5: Hounsfield Universal Testing Machine

After welding, there was a set of 18 samples. The tensile samples were prepared out of these welded sheets with the help of EDM wire cut. Wire cut method was chosen because it uses electric discharge to cut the material and there is no extra stress on the weld bead during metal cutting as in the case with conventional cutting methods. due to which error is minimized. The dimension maintained for tensile samples using EMD wire cut were according to the standard as given in Fig.3.6.

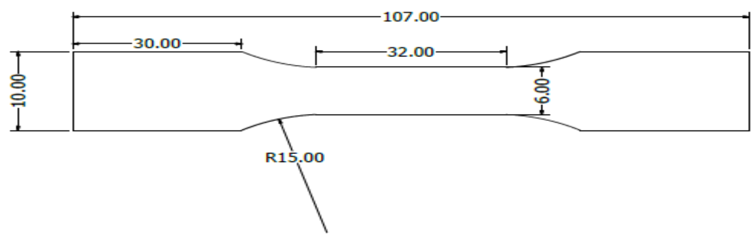


Figure 3.6: Tensile sample

These samples were then grinded using the surface grinding as there was uneven surface at the face of weld and also at the root. After grinding, these samples were applied with tensile loading on universal tensile testing machine to calculate their ultimate tensile strength.

3.7 Optical Microscopy

Samples were cut on EDM wire cut for calculation of heat affected zone. The welded samples were cut in a square shape of 10 mm X 10 mm. These samples were then used in optical microscopy. A mold was prepared of these samples which was then grinded using paper of range 180-600 grit size and polished. This mold was then analyzed under high magnifying optical microscope to calculate the heat affected zone of welded joint.

The samples were studied for the optical microscopy using the following magnifications: -

- 50 x
- 100 X
- 500 X

3.8 Hardness

Micro hardness was also calculated of these welded joints to check whether the welded area has become brittle or softened due to heating. We can also calculate heat affected zone or confirm the value of heat affected zone calculated by optical microscopy using micro hardness.

Chapter 4: Results and Discussion

4.1 CHEMICAL ANALYSIS

Three samples at different positions were taken for chemical analysis and average composition was measured. EDS analysis of sample was carried out. C/S analyzer. The standard deviation of analyzer is ± 0.20.

Table 4-1. Chemical Composition of Sample

Elements	Composition (Wt %)	Nearest Standard XCrNiTi 18 10	AISI 321
Fe	Balance	Balance	Balance
P	-	0-0.045	0-0.045
S	0.03	0-0.015	0-0.03
C	0.048	0-0.08	0-0.08
Ti	-	0-0.8	0-0.8
Si	0.41	0-1	0-1
Ni	9	9-12	9-12
Mn	1.05	0-2	0-2
Cu	0.37	-	-
Cr	17.01	17-19	17-19

The image of spectrum is shown in the figure 4.1.

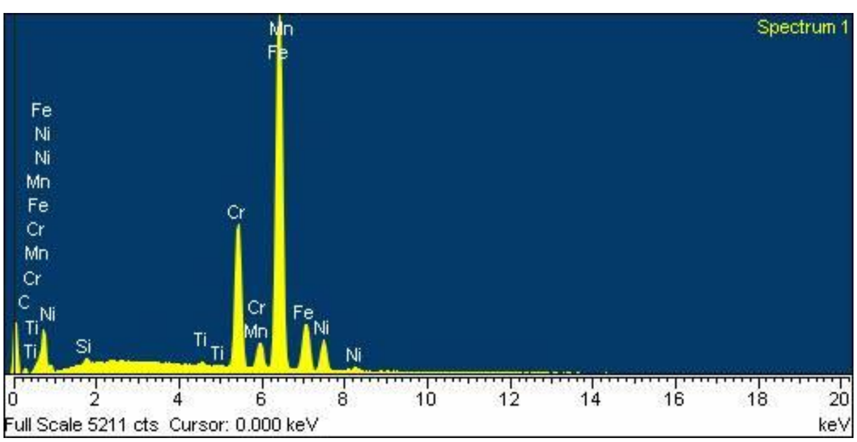


Figure 4.1: EDS Spectrum

4.2 Mechanical Testing

The samples were subjected to mechanical testing process and tensile tests were performed using UTS. Prior to testing of samples, the strength of parent material was also calculated using the same method. The strength of parent material was calculated to be 560 Mpa. The results obtained from UTS for tensile strength of the welded samples are given in table 4-2.

Table 4-2. Tensile Test Results

S.No	Voltage KV	Current mA	Speed mm/sec	Joint type	Strength MPa
1	80	8	10	Butt	385
2	80	8	10	Butt	400
3	80	9	20	Lap	440
4	80	9	20	Lap	395
5	80	10	30	Scarf	400
6	80	10	30	Scarf	421
7	90	8	20	Scarf	405
8	90	8	20	Scarf	422
9	90	9	30	Butt	505
10	90	9	30	Butt	483
11	90	10	10	Lap	350
12	90	10	10	Lap	386
13	100	8	30	Lap	394
14	100	8	30	Lap	413
15	100	9	10	Scarf	365
16	100	9	10	Scarf	310
17	100	10	20	Butt	440
18	100	10	20	Butt	415

4.3 ANOVA (Analysis of Variance)

After obtaining results of tensile strength using UTS, ANOVA was used for statistical analysis of results. ANOVA is a statistical technique used to assess the significance of process parameters on output responses. To find out impact of each input parameter at output response, sequential sum of squares (SS_A) was computed using the equation 1 [45].

$$SS_A = \sum_{i=1}^{3} \frac{A_i^2}{n} - \frac{(\sum_{j=1}^{N} T_j)^2}{N} \tag{1}$$

Where A is the process parameter, n is the total number of runs at a particular level, "i" is the level, T is value of response at each run, j is the number of run, and N is the total number of runs. Total sum of squares (SS_T) can be found using equation (2) [45].

$$SS_T = \sum_{j=1}^{N} T_j^2 - \frac{(\sum_{j=1}^{N} T_j)^2}{N} \tag{2}$$

A low value of variance (F-test ratio) for a given parameter shows its low impact on the outcome and vice versa. A p-value is the probability that a test would fail. A p-value less than 0.05 (5%) tells that there are 5% chances that test would fail or 95% chances that test would succeed. The percentage contribution of each parameter can be computed using equation (3) [45].

$$\%CR = \frac{SS - (df \times MSS_{Res})}{SS_T} \times 100 \tag{3}$$

4.4 ANOVA Calculations

The ANOVA calculations are done using the above mentioned equations and then p-test and f-test is performed to find out the impact of each parameter individually on the desired output. These are lengthy calculations which can be easily using statistical software" MINITAB". Th Taguchi design was created in Minitab using input parameters and L9 array was formed. The tensile strength was set as output parameter. ANOVA general linear model was implemented. The results obtained from Minitab calculation were tabulated and are given in table 4-3 and 4-4.

Table 4-3: ANOVA General Linear Model: Strength versus input variables

Factor	Type	Levels	Values
Voltage	fixed	3	80, 90, 100
Current	fixed	3	8, 9, 10
Speed	fixed	3	10, 20, 30
Joint type	fixed	3	Butt, Lap, Scarf

Table 4-4: Analysis of Variance for Strength, using Adjusted SS for Tests

Source	DoF	Seq SS	Adj SS	Adj MS	F	P	Percentage contribution
Voltage	2	3817.3	3817.3	1908.7	3.92	0.06	11.28027068
Current	2	760.3	760.3	380.2	0.78	0.487	2.246716213
Speed	2	16069	1669	8034.5	16.49	0.001	47.48540949
Joint Type	2	8808.3	8808.3	4404.2	9.04	0.007	26.02887073
Error	9	4385.5	4385.5	487.3			12.95932389
Total	1	33840.5					

S= 22.0744	R-Sq = 87.04 %	R-Sq (adj) = 75.52%	R-Sq (pred) =48.16%

Percentage contribution of each parameter is also calculated using Minitab which tells us about the impact of every parameter on desired output. The result shows that maximum impact on tensile strength is of welding speed and is followed by joint type, which also plays a vital role in deciding its strength. The results also show that voltage effect is less and the impact of current is minimum of these four input parameters. The same is justified from the tensile results shown in the table 4-2.

4.4.1 Regression Equation

The regression equation for maximum strength is also calculated using Minitab and is given as:

Strength = 407.17 - 0.33 Voltage_80 + 18.00 Voltage_90 - 17.67 Voltage_100 - 4.00 Current_8
+ 9.17 Current_9 - 5.17 Current_10 - 41.17 Speed_10 + 12.33 Speed_20
+ 28.83 Speed_30 + 30.83 Joint type Butt - 10.83 Joint type Lap
- 20.00 Joint type Scarf

The graphs of ANOVA obtained from Minitab analysis are shown in Fig. 4.2.

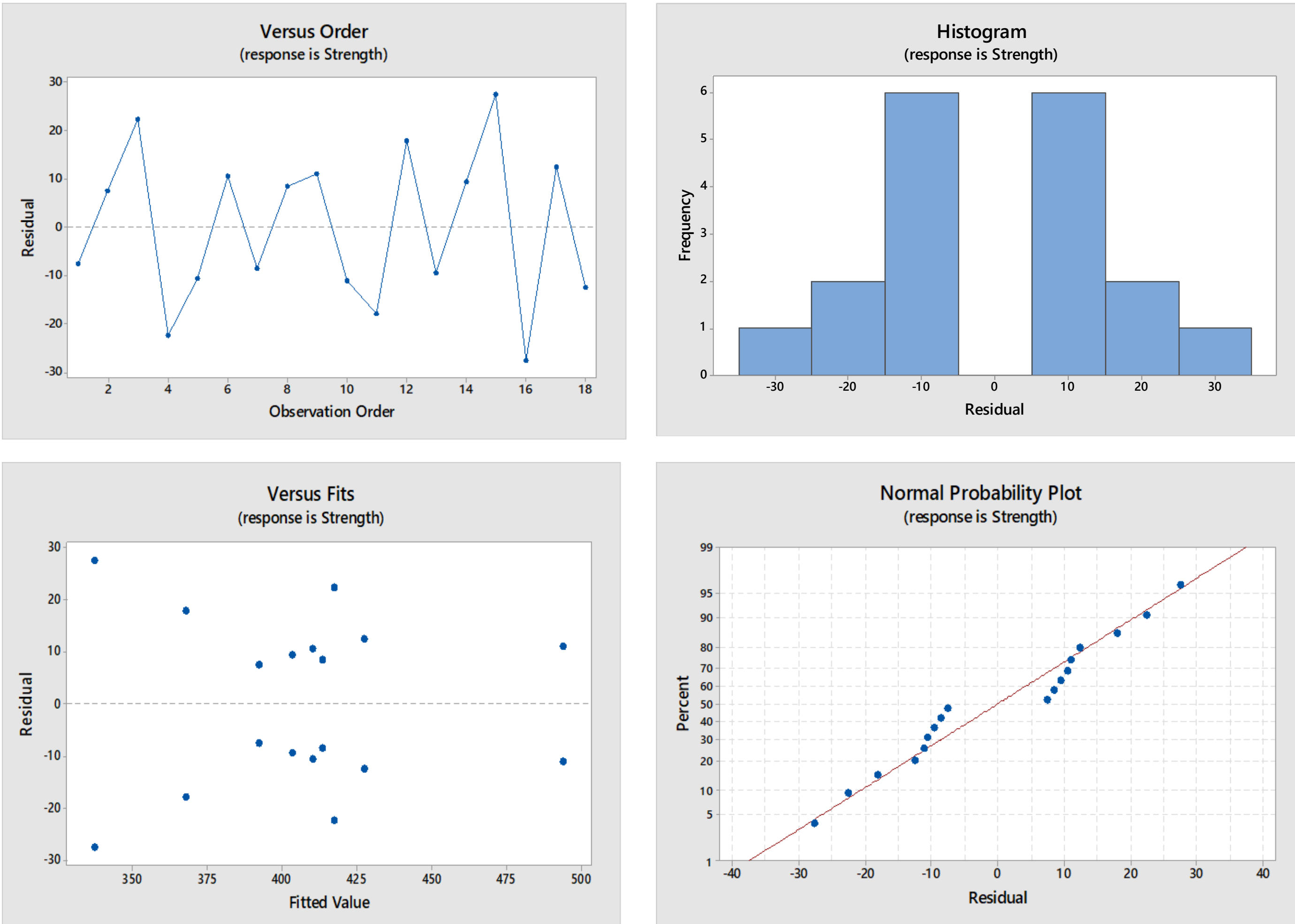


Figure 4.2: ANOVA Distribution Graphs

4.5 Taguchi Analysis

After performing ANOVA, another statistical test which was performed on sample results was Taguchi's analysis. This analysis was also done using Minitab. The response selected for desired outcome was "Larger is better" as we require high strength of our welded joints. The results were tabulated and are shown in table 4-5 and 4-6

Table 4-5: Response Table for Signal to Noise Ratios (Larger is better)

Level	Voltage	Current	Speed	Joint Type
1	52.17	52.1	51.21	52.78
2	52.49	52.24	52.44	51.92
3	51.73	52.05	52.75	51.69
Delta	0.76	0.19	1.53	1.1
Rank	**3**	**4**	**1**	**2**

Table 4-6: Response Table for Means (Larger is better)

Level	Voltage	Current	Speed	Joint Type
1	4.6.8	403.2	366	438
2	425.2	416.3	419.5	396.3
3	389.5	402	436	387.2
Delta	35.7	14.3	70	50.8
Rank	**3**	**4**	**1**	**2**

The results of these two tables give us the information regarding the effect of each variable and is ranked in order from 1 to 4 depending upon its impact on strength. Both the tables show that maximum impact on outcome is of welding speed having been ranked “1”, followed by joint type which is ranked “2”. Voltage stands at 3 while effect of changing the input current is having the least effect on desired output. These results are in conformance with ANOVA and also with tensile strength results. The graphs obtained from Minitab for Taguchi’s Analysis are shown in figure 4.3.

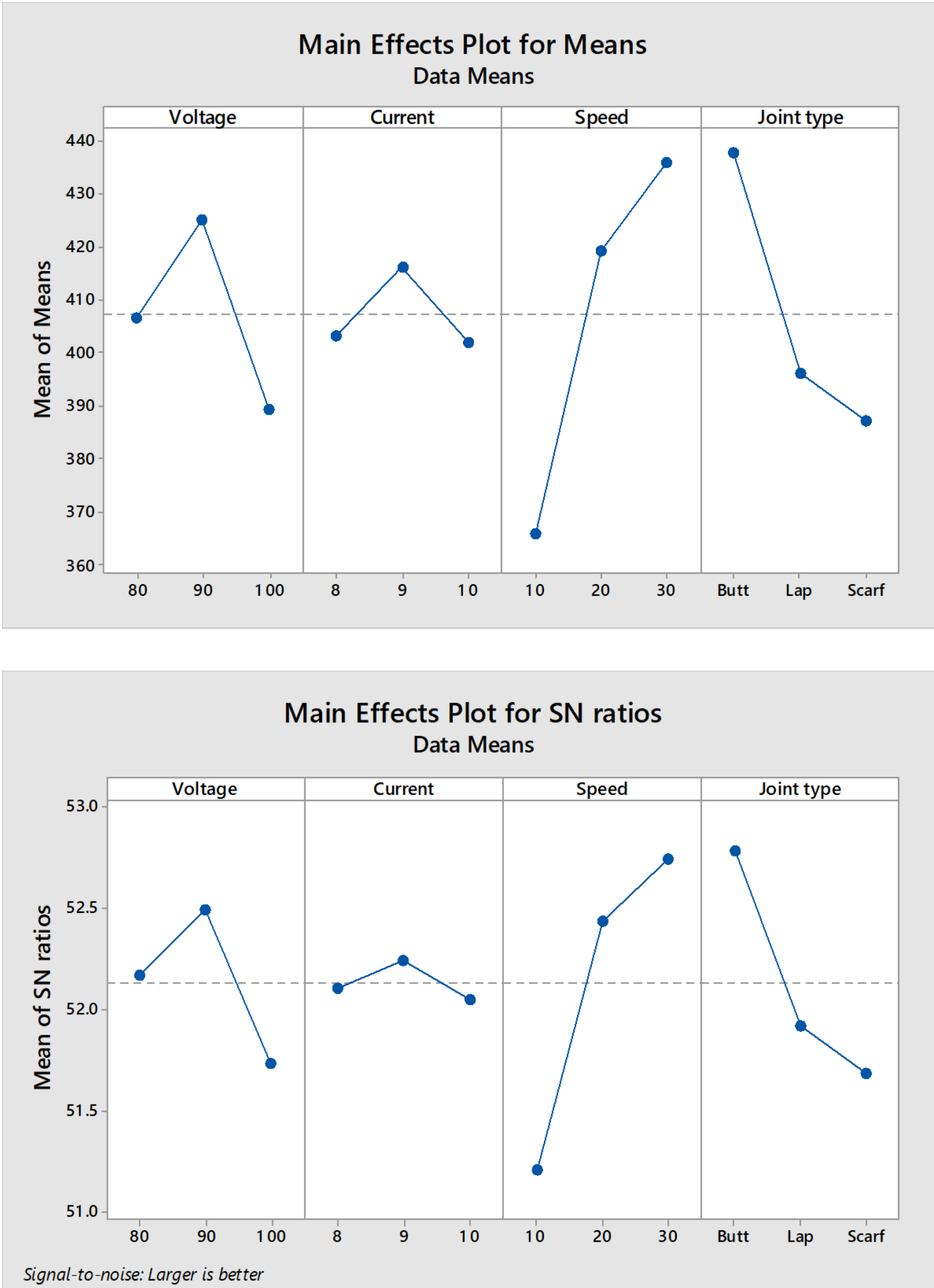


Figure 4.3: Main Effects Plots (Taguchi Analysis)

The main effect plots for signal to noise ratio and for means also give us the best possible combination of our input variables which will produce the best results, or in other words the welding parameters are optimized for best possible outcome. By looking at the graph, we can observe that both out graphs peak at (Higher strength value):

Voltage	**90KV**
Current	**9mA**
Welding speed	**30mm/sec**
Joint Type	**Butt**

By using these parameters, maximum strength can be achieved. The same is also shown in table 4-2 (Tensile strength results).

4.6 Optical Microscopy

After calculating the tensile strength, samples were cut on EDM wire cut for calculation of heat affected zone and microstructure analysis. The welded samples were cut in a square shape of 10mm X 10 mm. Images were taken using high resolution microscope of the dendrites of SS 321. The images of optical microscope are shown in the Fig. 4.4.

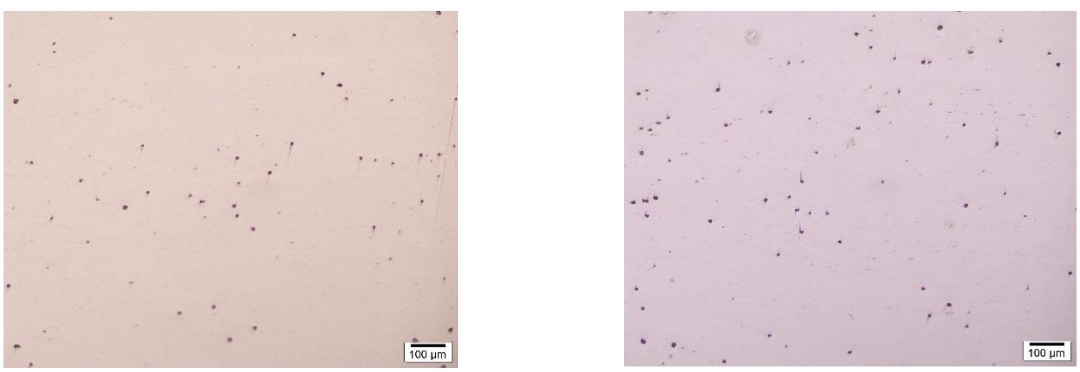
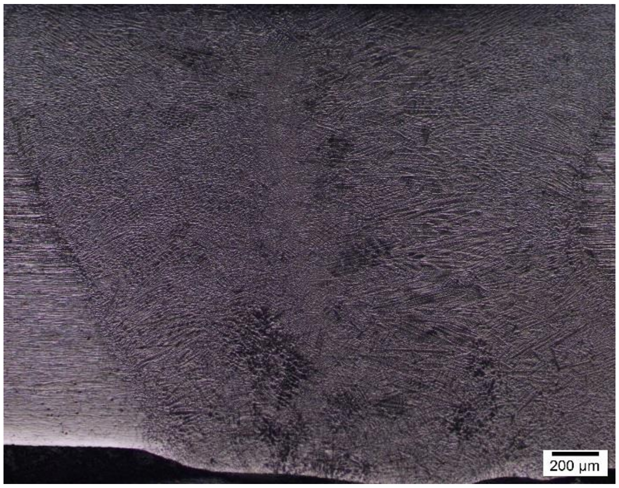
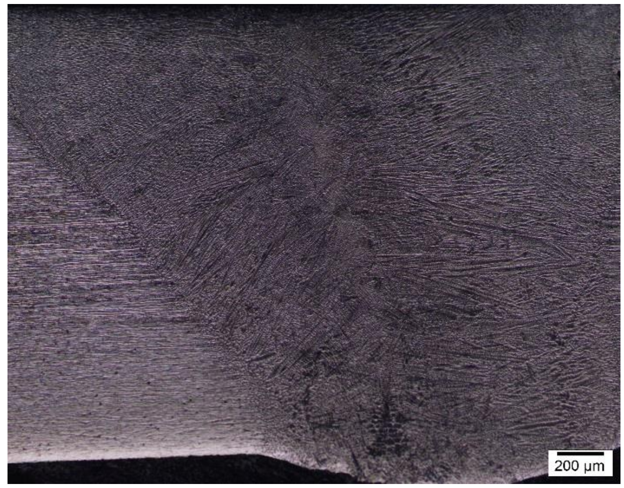
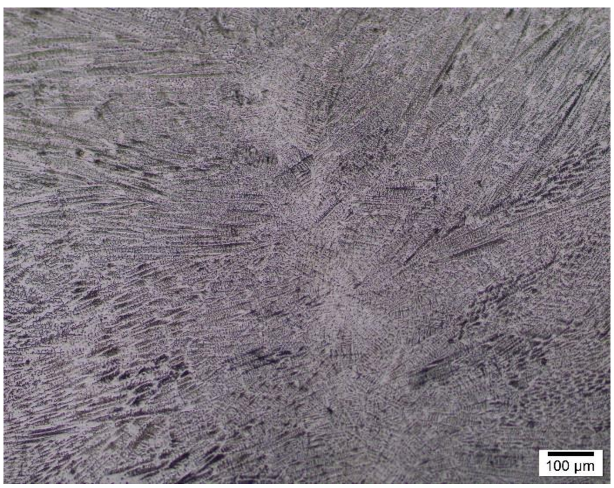
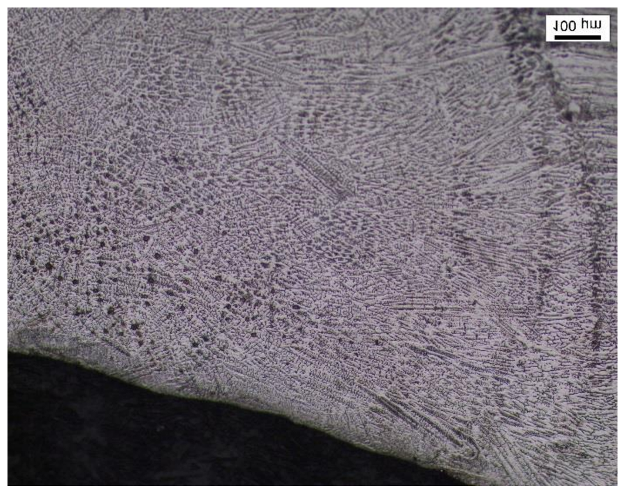
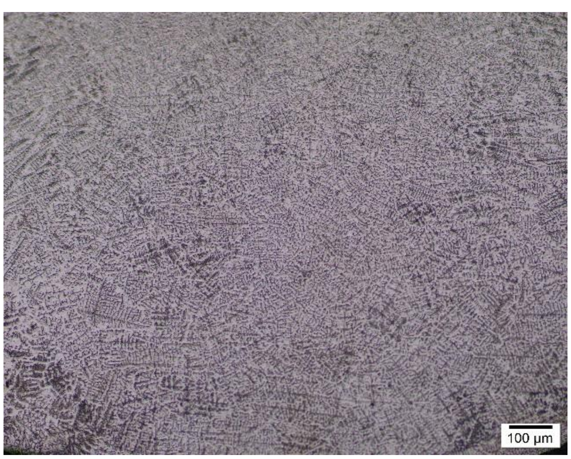
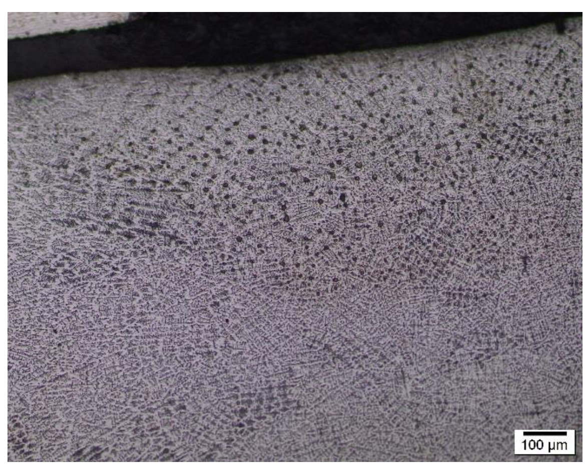


Figure 4.4: Microstructure of welded sample

Similarly, images were taken of the weld zone to differentiate the microstructure. The images for weld zone are shown in figure 4.5.

Sample 1	**Sample 2**
	
Sample 3	**Sample 4**
	
Sample 5	**Sample 6**
	

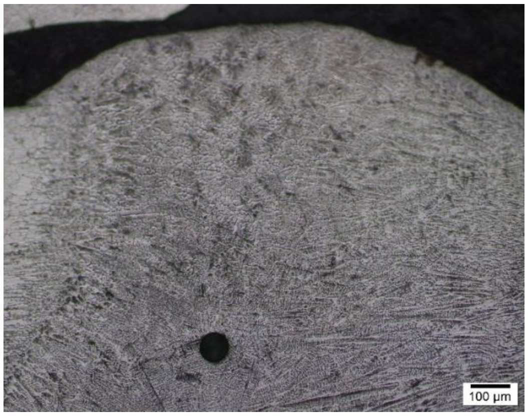
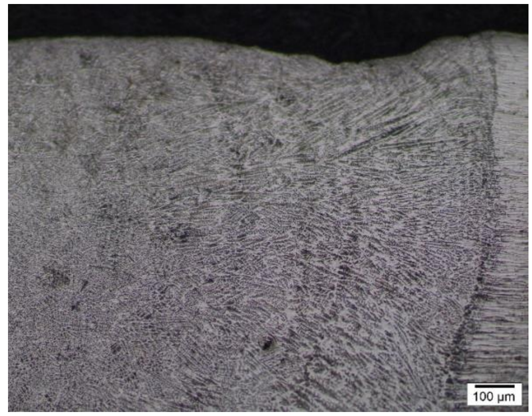
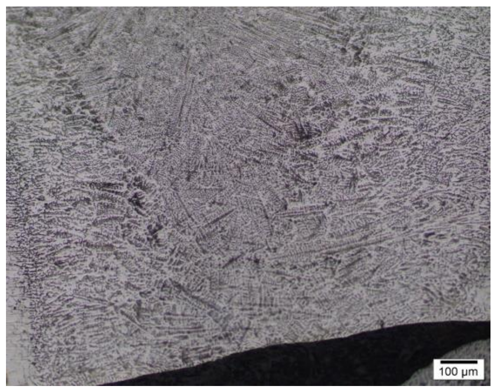
Sample 7	**Sample 8**
	
Sample 9	
	

Figure 4.5: Microstructure of welded region

These figure shows the difference of structure between parent material (Austenite) and the welded portion.

The length of heat affected zone was calculated as it is a major factor which effects the strength of the material. The images observed on microscope for HAZ are shown in Fig 4.6.

Figure 4.6: Heat Affected Zone Calculation

The values calculated of heat affected zone Depth of weld and width and weld are given in table 4-7. The value of width was taken at three different points, weld top, weld centre and bottom of weld.

Table 4-7: Heat Affected Zone

S. No	Voltage (KV)	Current (mA)	Speed (mm/s)	Joint Type	UTS (Mpa)	Weld Width (μ)			Weld Depth (μ)	HAZ (μ)
						Top	Centre	Root		
1	80	8	10	Butt	385	3834	2408	3523	2050	496
					400	3850	2476	3611	2065	558
2	80	9	20	Lap	440	3472	2603	1983	1950	398
					395	3503	2585	2011	1990	358
3	80	10	30	Scarf	400	3138	2544	1985	2016	682
					421	3109	2521	1957	2002	785
4	90	8	20	Scarf	405	3039	2605	2605	2019	480
					422	3105	2567	2510	2011	660
5	90	9	30	Butt	505	2688	1757	1465	2038	372
					483	2655	1700	1510	2025	332
6	90	10	10	Lap	350	3039	2560	2145	2095	700
					386	3100	2621	2185	2115	850
7	100	8	30	Lap	394	3591	2795	2560	2320	357
					413	3549	2820	2508	2285	417
8	100	9	10	Scarf	365	3290	2865	2196	2190	789
					310	3308	2898	2210	2205	855
9	100	10	20	Butt	440	2274	1716	1347	2088	550
					415	2310	1650	1265	2109	605

4.7 Profile Hardness

The samples were then subjected to micro hardness to find their profile hardness. The value of hardness was calculated in Hv. The calculation was started from the center of the weld with an increment of 0.13 mm in length towards the base metal. The indented samples are shown in the Fig 4.7.

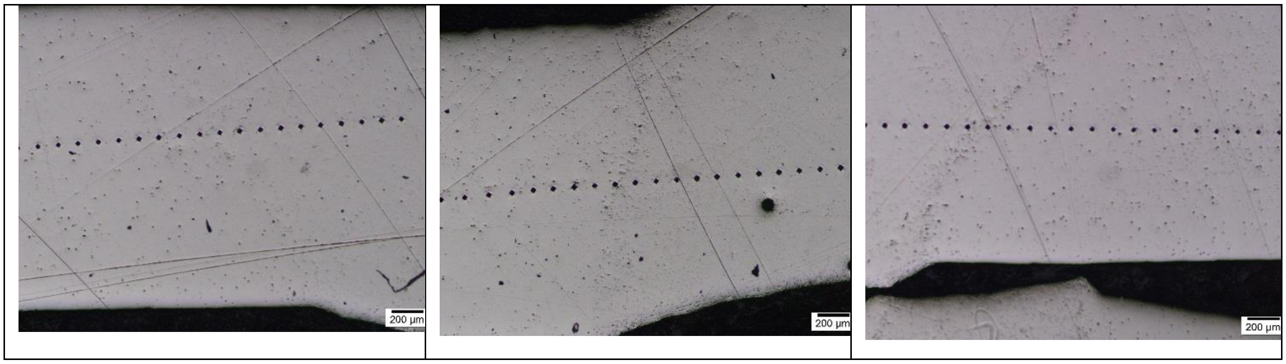
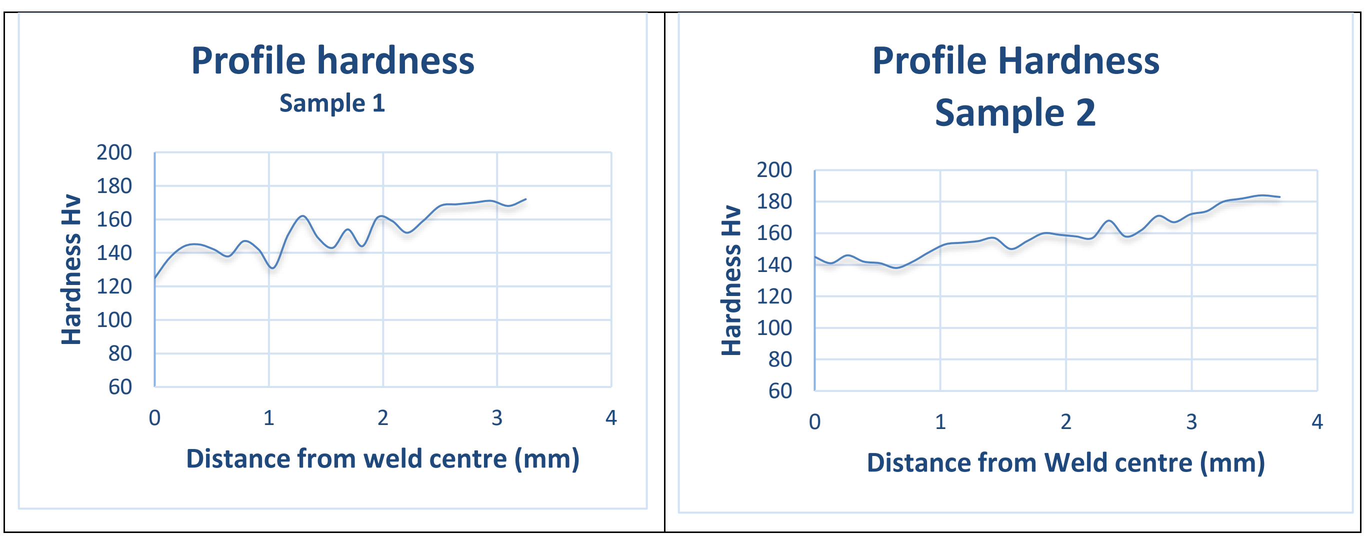
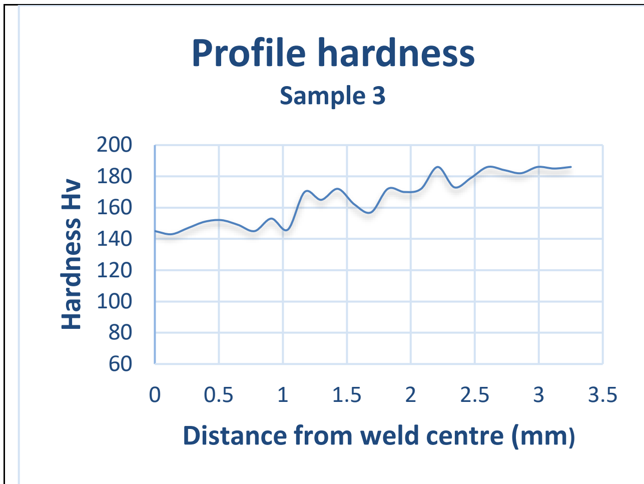
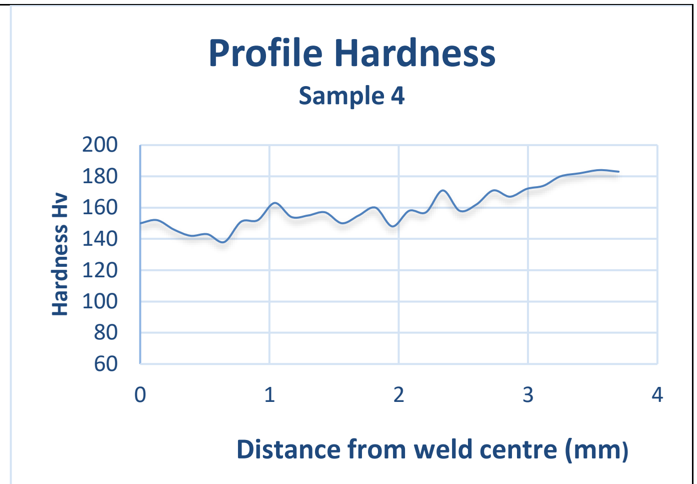


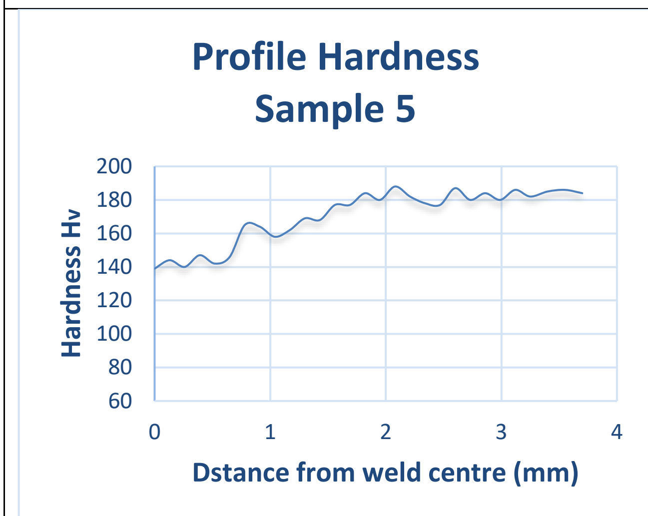
Figure 4.7: Profile Hardness images

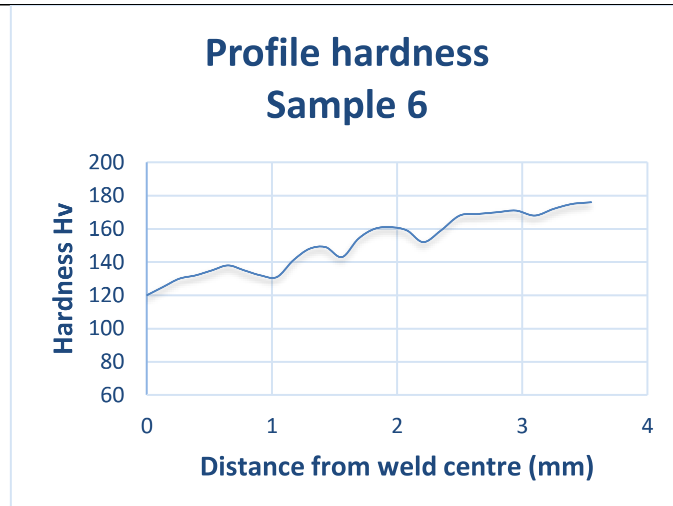
The values of hardness were then plotted on a graph to depict the difference of hardness values in melt pool and base metal. It was observed that hardness in melt pool was reduced as compared to base metal or we can say that samples were annealed in welded area which is according to literature. The value of hardness increased constantly as we approached the base metal. By these values of micro hardness, we can also find out the heat affected zone of welded samples. The graph showing hardness profile of all the samples is given in Fig 4.8.

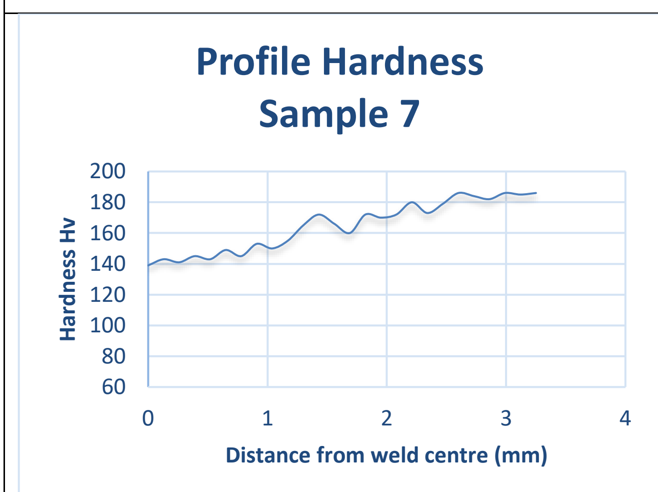


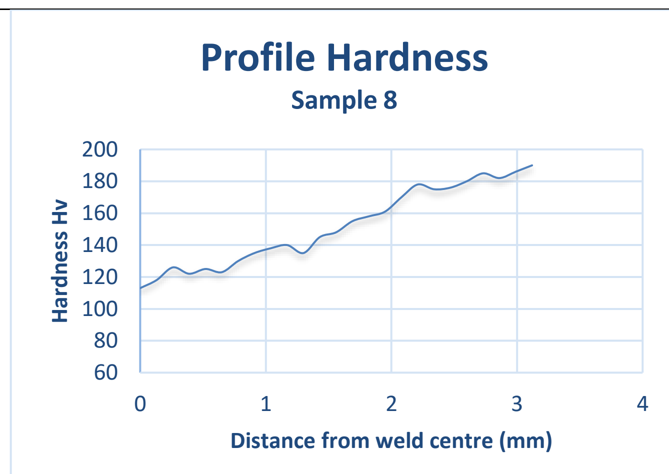

Profile hardness
Sample 3
Hardness Hv
200
180
160
140
120
100
80
60
0
0.5
1
1.5
2
2.5
3
3.5
Distance from weld centre (mm)


Profile Hardness
Sample 4
Hardness Hv
200
180
160
140
120
100
80
60
0
1
2
3
4
Distance from weld centre (mm)


Profile Hardness
Sample 5
Hardness Hv
200
180
160
140
120
100
80
60
0
1
2
3
4
Dstance from weld centre (mm)


Profile hardness
Sample 6
Hardness Hv
200
180
160
140
120
100
80
60
0
1
2
3
4
Distance from weld centre (mm)


Profile Hardness
Sample 7
Hardness Hv
200
180
160
140
120
100
80
60
0
1
2
3
4
Distance from weld centre (mm)


Profile Hardness
Sample 8
Hardness Hv
200
180
160
140
120
100
80
60
0
1
2
3
4
Distance from weld centre (mm)

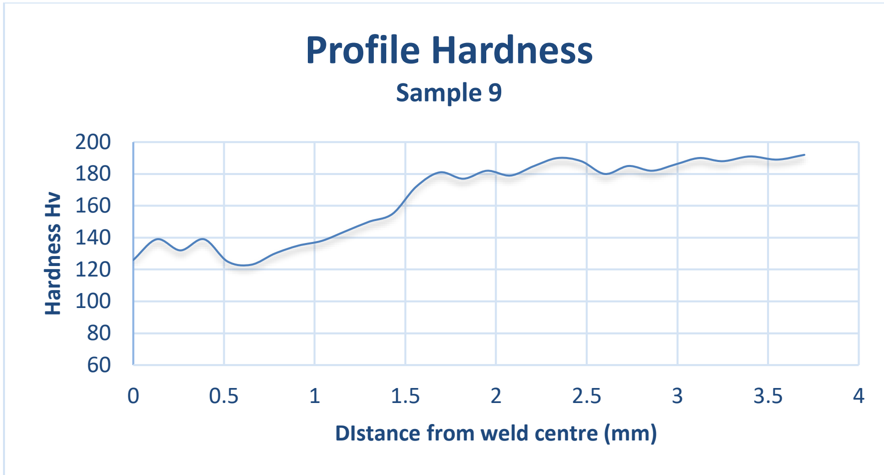


Figure 4.8: Profile hardness of welded samples

4.8 Confirmation Test

After finding the optimum parameters and performing of statistical analysis of results, these parameters were again verified to confirm the test. New samples were welded using the best and worst parameters as shown:

Table 4-8: Confirmation Test

S. No	Best Parameters	Worst Parameters
Speed	30 mm/sec	10 mm/sec
Current	9 mA	10 mA
Voltage	90 KV	100 KV
Joint Type	Butt	Scarf

The welded samples were again cut for the tensile sample to check its strength and also the heat affected zone. The result of this test was similar to the one performed earlier giving tensile strength of 498 MPa which confirms the results obtained by earlier experiments for best results. Similarly worst parameters sample was also cut for tensile Sample and HAZ calculation. The result obtained was 310 MPa for tensile strength which also confirms our analysis.

Chapter 5 Conclusion

1. 9 X samples were prepared of material SS 321 and were welded using Taguchi's design of experiment having Current, Voltage, Speed and joint type as input variables. The required outcome was tensile strength and minimum heat affected zone. Statistical analysis was performed on the results obtained which shows the following optimized input parameters for welding:
   - ✓ Current 9mA
   - ✓ Voltage 90KV
   - ✓ Speed 30mm/sec
   - ✓ Joint Type Butt
2. Regression equation was calculated using Minitab software which gives the equation for best possible results we can achieve using these variables.
3. ANOVA shows that maximum impact on output strength is of welding speed (47.5%) followed by joint type (26 %). These play important role in deciding the welding strength and need to be optimized for further improvement.
4. Taguchi's analysis gives the rank of parameters which have major impact on outcome. The results show that Welding speed in ranked first followed by joint type and accelerating voltage. The current is ranked fourth in the analysis and has least effect on outcome.
5. Profile hardness of samples show that material is annealed in melt pool as its hardness is reduced in that area and increases as we approach the parent material.
6. Heat affected zone plays major role in strength of joint, less hat affected zones have high strength and vice versa.
7. The microstructure in the melt pool changes to cast structure and is different from the parent material.

5.1: Recommendations

- Number of weld passes should also be increased to observe their effect.
- Joining of dissimilar materials should be tried using same design of experiment
- Effect of change in vacuum can also be studied and electron beam welding takes place under vacuum.
- Shooting distance has lag effect on weld quality which can also be studied along with other input variables

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