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A review on Electron Beam Welding process

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Abstract. Electron Beam Welding is an unconventional manufacturing technique widely used in the Aerospace and Defense industries mainly due to the Narrow Fusion Zone (FZ) generated as less metal is melted which leads to less distortion and less amount of heat, as opposed to the other welding processes such as TIG welding and Arc welding. As a result, the solidification of the Weld Joint is in several orders much higher. The Electron Beam Welding process is complex in nature and is controlled by large number of parameters. Parameters such as Accelerating Voltage (U_a), Beam Current (I_f), Depth of Penetration (H), Beam Focal Diameter (d_{f0}) and Welding Speed (v) are part of the Electron Beam Parameters, while Thermo-physical and Chemical properties of the Material and Workpiece Thickness are part of the Parameters influencing Welding Features. This paper also reviews various optimization methods applied by researchers and finally outlines the recommendations and future trends in Electron Beam Welding.

Keywords: Manufacturing, Electron Beam Welding, Unconventional Manufacturing Techniques, Fusion Welding, Trends in Manufacturing.

1. Introduction

The *Electron Beam Welding* process is a *Fusion Welding* process as the metal to metal joint forms in liquid or molten state. This type of welding process is also classified as a new welding process as it uses the kinetic energy of fast-moving electrons to fuse two metal pieces at its joint [1]. The German physicist Karl-Heinz was the first to conceive this welding process in 1949. Generally, Aerospace, Defense, Automobile, Medical and other industrial parts that require extremely low-distortion welds are feasible and easily achieved by this process. The quality of the *Weld Joints* depends heavily on the metallurgical properties, welding parameters and welding joint designs. The *Electron Beam Welding* process is generally cost effective and simple as filler materials are not typically used due to the possibility of adulteration of the metallurgical properties within the *Weld Joint*. However, as with any rule there are exceptions. Welding of the 6061-series aluminum alloys is quite difficult without altering the weld pool by using filler material, which is true even for other welding processes. The 6061-series Aluminum alloys which is widely used in the Aerospace industries due to their high strength, workability, good corrosion resistance and weight is composed majorly of Silicon and Magnesium. It is the presence of Magnesium within such alloys that results in the development of oxide films on the surface of the weld which can lead to incipient cracking which is not desirable. Hence, considerable modifications to the weld pool must take place. Doing this however, will result in a drop in the mechanical strength of the *Weld Joint*. The *Electron Beam Welding* process is a versatile technology that takes place in high vacuum working conditions, where thin section welding is feasible. This results in the mechanical strength of the *Weld Joint* being greatly preserved unlike other conventional welding processes.



In comparison with other methods of joining two metal workpieces, *Electron Beam Welding* can be characterized by the following.

- An extremely high-power density of 100 kW/mm^3 is achieved at the focus of the beam [5].
- Materials as thick as 15cm or 5.91in can be welded with ease, and the distance between the welding gun and workpiece can be as great as 0.7m or 27.56in [6].
- Due to higher welding speeds, narrow welds and HAZ with minimal distortion to the workpiece is easily achieved [5].
- The surrounding material of the workpiece stays relatively cool due to localized heat input. The *Electron Beam Welding* process has a HAZ approximately less than 5% of a similar TIG weld [7].
- Very less or no post-weld machining is required due to the high strength and minimal to no distortion at the *Weld Joint*. Thus, making it suitable for precision welding parts [7].
- High-quality *Weld Joints* with little to no oxidation is achieved as the welding process is conducted in a vacuum environment which is free from gas contamination [3][7].
- The innate ability to weld workpieces of two different melting points or dissimilar metals is perhaps, the biggest advantage of the *Electron Beam Welding* process [7].
- Heat treated components, refractory metals such as Titanium and even reflective metals such as Platinum can be welded with relative ease [7].
- High depth to width ratio in the *Electron Beam Welding* process ranges from 10:1 to 40:1 with weld *Depth of Penetrations (H)* ranging from 0.127mm (0.005in) to 50mm (2in) [7].
- This process requires a single pass through of the electron beam to complete the *Weld Joint* formation which result in cost and time savings by 50% unlike other welding processes such as the TIG, MIG and Arc-welding [9].
- Higher quality welds that are highly reproducible and consistent are achieved by controlling the weld parameters with relative ease [5].

The Electron Beam machining market as of 2019 is estimated to be worth USD 181 million and is expected to be worth USD 212 million by 2024 [11] as shown in Figure 2. The Compound Annual Growth Rate (CAGR) for this market from 2019 to 2024 is expected to be about 3.2% as shown in Figure 1. The increasing demand of such machineries in Automotive, Aerospace and Defense, Medical, Oil and Gas, Nuclear and many industrial applications has been a major propelling factor in the expansion of the Electron Beam machining market according to various research studies. The increasing need to design and develop structurally stronger parts and leak-proof fuel tanks for vehicles suggest that the Automobile industry will become the biggest adopter of the Electron Beam machining market in the foreseeable future. Analysis shows that the welds produced by the *Electron Beam Welding* process retains the structural strength of the workpiece relatively much more than other welding processes. Some of the key market players that have dominated the global Electron Beam machining market are the Global Beam Technologies (Germany), Mitsubishi Electric (Japan) and Pro-beam (Germany). According to the research by the Ref. [11], in terms of application, the Electron Beam machining market is dominated by welding, surface treatment and drilling respectively.

Despite the growing market share of the Electron Beam machining, the *Electron Beam Welding* process is not shy of any drawbacks. Some of them are as follows.

- The size of the workpiece to be welded by the *Electron Beam Welding* process is still restricted by the size of the vacuum chamber [8].
- The initial outlay or setup cost is very high. Maintenance cost associated with such an equipment is also very high. The usage of such equipment requires labor of high skill and experience [7].
- Although the electron gun requires *High-Vacuum Pressure (P_s)*, the *Vacuum Pressure (P_s)* in the rest of the chamber is not required to be so high. The vacuum chamber plays an excellent

role in protecting the operator from X-ray radiations. However, additional safety standards must be implemented in the working environments of the *Electron Beam Welding* equipment for the operators and working personals in the case of failure [10].

- Majority of *Electron Beam Welding* machineries are provided with manipulators (x & y axes along with rotary tilt). Hence this allows for high quality 2D weld. 3D weld is difficult to achieve due to the nature of construction of the equipment [8].

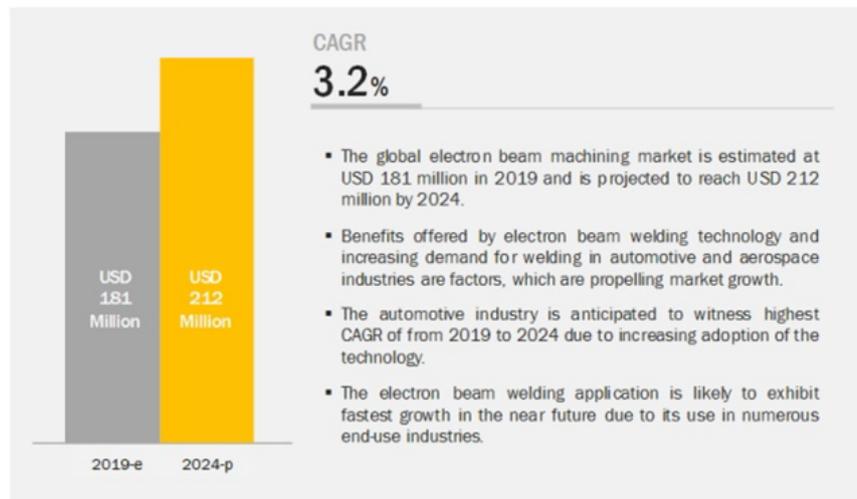


Figure 1. Projected increase in CAGR for Electron Beam Machining Equipment across the globe, Ref. [11]

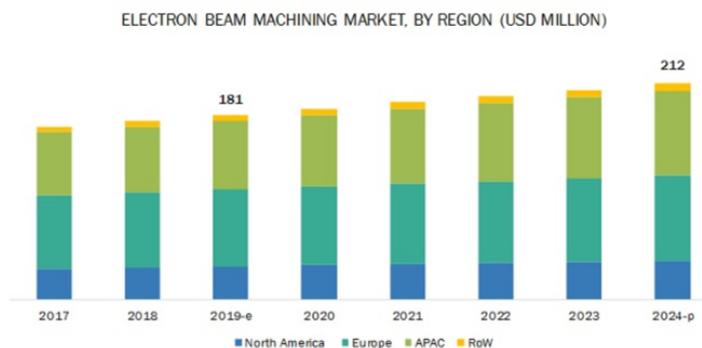


Figure 2. Global market statistics for Electron Beam machining Equipment, Ref. [11]

Despite the rapid development of the competitive *Laser Beam Welding* process, the *Electron Beam Welding* process still remains indispensable due to its possibility of obtaining greater *Depth of Penetration (H)* and purity of the weld.

2.Characterestics of Electron Beam Welding

The principle of the *Electron Beam Welding* is very similar to that of the Electron Beam Machining. The Electron Beam Machine is made up of three major components that may have separate vacuum chambers. They are as follows.

- *Beam Generation*
- *Beam Manipulation*
- *Forming and Working Chamber*

Beam Generation

Here, the electrons are produced by passing current to the electron gun (Cathode) and heating it up to 2000°C in a vacuum chamber. The electron gun operates at high voltages in the order of 60kV to 150kV to accelerate the electrons. The electrodes geometry here within the inter-electrode space defines the electron trajectory. In between the cathode and the anode is a modulating electrode known as the “Wehnelt cylinder” [2], which regulates the electron flow. As the electrons pass through the anode, the electron beam converges and continues to move by inertia as it slowly diverges. In this manner the anode forms the electron jet by accelerating the electrons.

Beam Manipulation

The necessary power density is obtained by the electron beam for welding by passing it through the adjacent alignment and focusing system. The alignment and focusing system consist of a deflection coil and a stigmator coil. The deflection coil facilitates in maintaining the oscillating motion of the electron beam. The deflecting coils are then used to focus the electron beam at the required spot. This unit directs high velocity electron beam to the weld cavity where its kinetic energy converts into high energy due to collision. The stigmator coil helps rectify any aberrations of the magnetic lenses. The electron beam is then directed towards the magnetic lenses. These are a series of lenses that are used to absorb a series of electrons and also does not allow a divergent electron to pass through it.

Forming and Working Chamber

Each accelerated electron in an electron beam stores kinetic energy. While the kinetic energy stored in an individual electron is not very significant, in mass they can contribute to a very large amount of kinetic energy. Since electrons transfer their energy into a very thin layer of solid, the power density of the electron beam can be very high in the order of 10^4 to 10^7 W/mm². When the electron beam strikes the workpiece, the huge amount of kinetic energy developed within the accelerating electrons is converted into heat energy of the order of 10^5 to 10^7 W/mm². It has been identified that the heat energy produced from the kinetic energy of the fast-moving electrons is sufficient to melt the workpiece metals at the joint and fuse them [4] as shown in Figure 3.

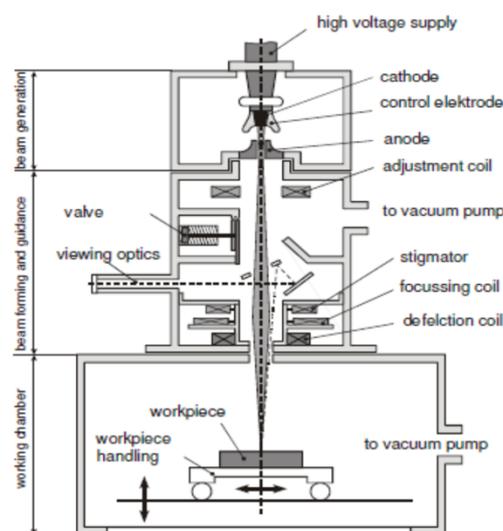


Figure 3. Schematic Diagram of Electron Beam Welding, Ref. [2]

One of the most incisive characteristics of the *Electron Beam Welding* process is its operating environment in vacuum. There are majorly three reasons as to why the *Electron Beam Welding* process must be conducted in a *High-Vacuum* environment.

The *First* reason is rust. Many metals will oxidize, rust or even burn when heated to a higher temperature in a normal atmosphere. The oxygen from the air reacts with the metal to form oxides. This weakens the weld and possibly damages the base metal. In the case of other welding techniques such as the TIG welding process or MIG welding process, an inert gas generally argon is used to shield the weld until it cools to prevent this problem.

The *Second* reason is due to the presence of atmosphere particles. The electron beam is made up of millions of fast-moving electrons. Each electron weighs less than one ten-thousandth of what a Nitrogen or an Oxygen atom weigh. If an electron were to strike any of these atoms, it would result in a deviation from its path and thus a loss in energy due to collision. Hence, the electron beam will no longer be localized but rather scattered.

The *Third* reason is lightning. The electric gun works by accelerating electrons to obscenely fast speeds. It does this by pulling the electrons using a strong electric charge measured in thousands of volts. This electric potential is so high that it will create electrical arcs between the electron emitter and the acceleration grid. These arcs can pose a high risk of safety to the welder or the operator. As a result, the *Electron Beam Welding* process is conducted in *High-Vacuum* to prevent arcing. There are majorly three vacuum levels in *Electron Beam Welding*. They are as follows.

- a) *High-Vacuum welding* – Here welding occurs in the same vacuum chamber as *Beam Generation* to produce the highest quality welds. These are extremely expensive mainly due to operating and maintenance costs.
- b) *Medium-Vacuum welding* – The idea of this welding is to reduce pump down time by welding in a separate chamber.
- c) *Non-Vacuum welding* – Welding is conducted at near atmospheric pressures. Here, the quality of the weld is lowest.

When pertaining to the *Electron Beam Welding* process, whenever an electron beam is stopped by the workpiece, X-rays are generated. The power density of the electron beam is inversely proportional to the beam diameter squared and directly proportional to the Beam Voltage and Current [13] as given in Equation 1. The X-rays are proportional to the power density of the electron beam. Also, it has been determined that penetration is directly proportional to the power density as given by Equation 2. However, the total energy converted by the electron beam upon bombardment with the workpiece to X-rays is only a few percent of the total electron beam energy [12].

$$D \propto VI/d^2 \quad (1)$$

Where, V = Beam Voltage

I = Beam Current

d = Beam Diameter

$$X \propto D \quad (2)$$

Where, X = Depth of Penetration

D = Power Density

According to Ref. [13], all the electrons in the electron beam has nearly the same amount of energy and hence will produce a significant number of X-ray photons having energies equal to the accelerating voltage. The energy of these X-rays is given as follows.

$$E_m = \frac{hc}{\lambda} = h\nu \quad (3)$$

Where, E_m = Maximum photon energy

h = Planck's constant

c = Speed of light

$$E_m = eV \quad (4)$$

Where, e = Electron charge

V = Accelerating voltage

While the operators are generally protected from the minuscule amounts of radiation during the *Electron Beam Welding* process due to the presence of a *High-Vacuum* chamber, the X-rays offers a means of measuring the operating voltage of an electron beam by using an energy dispersive spectrometer to measure the X-ray spectrum generated by an electron beam and determining the voltage from the high energy cut-off [13].

3. Welding Process Comparison

The *Electron Beam Welding* process is used to cater to a very specific need in an industry due to various parameters as follows [14].

- *Material Type* – While materials such as low-carbon Steel can be welded with ease by most welding processes, High-alloy Steels, Aluminum, Titanium can be welded with ease by the *Electron Beam Welding* process.
- *Thermal Conductivity* – Materials with high *Thermal Conductivity* can be welded with ease, as the heat generated by the electron gun is more than sufficient to weld just about any material.
- *Coefficient of Thermal Expansion*–Materials with high *Coefficient of Thermal Expansion* leads to differential expansion and contraction on heating and cooling respectively during the welding. The *Electron Beam Welding* process can handle welding of such materials with ease.
- *Oxidation* – Due to the presence of vacuum chamber, the materials welded by this process is protected from *Oxidation*.
- *Flux Residue*–This process does not use flux and thereby prevents any form of possibility of the weld properties being affected.
- *Crack Sensitivity*– The presence of vacuum chamber helps mitigate the formation of residual Hydrogen and thereby prevent cracking when welded at high temperatures.
- *Material Thickness, Shape and Size* – This process is not limited to a specific workpiece thickness, nor is it limited to the shape of the workpiece. The size of the workpiece however, is the only constraining parameter when utilizing this process as it is restricted to the size of the vacuum chamber.
- *Process Economy* – This process is capable of welding most materials in a single pass though. With the right set of process parameters, this process can easily avoid the need for further machining operations, thereby bringing the *Process Economy* down.

The core objective is to determine how the *Electron Beam Welding* process fares against other welding process.

Table 1. Welding Process Comparison Ref. [14]

Process	Sheet and Plate	Large Pipe and Cylinder	Lap Joint	Butt Joint in Tubes	Butt Joint in Bars	Attachments	Fillet or T-Joint
SMAW	Yes	Yes	Yes	Yes	No	Yes	Yes
SAW	Yes	Yes	No	No	No	No	Yes
GTAW	Yes	Yes	Yes	Yes	No	Yes	Yes
PAW	Yes	Yes	Yes	Yes	No	No	No
GMAW	Yes	Yes	Yes	Yes	No	Yes	Yes
FCAW	Yes	Yes	Yes	Yes	No	Yes	Yes

LBW	Yes						
EBW	Yes						

Table 1 clearly indicates that both the *Electron Beam Welding* and the *Laser Beam Welding* process are highly capable of welding any geometry due to their localized heating and good control of *Depth of Penetration (H)*. This certainly wouldn't alone be enough to justify the use of *Electron Beam Welding* in the industry.

The process of *Laser Beam Welding* consists of a focused beam of photons that are directed to the surface of the part to be welded. Similar to *Electron Beam Welding*, the rapid heating of the laser allows for a shorter beam interaction time, resulting in a smaller HAZ [15].

However, the shortcomings of the *Laser Beam Welding* process outweigh those of the *Electron Beam Welding* process making *Electron Beam Welding* more suitable for most welding applications. Some of these disadvantages are as follows.

- In *Laser Beam Welding* process, gas contamination is possible, unlike in the *Electron Beam Welding* process.
- Smaller *Depth of Penetration (H)* than *Electron Beam Welding* process.
- Cannot weld dissimilar or refractory materials.
- Unclean welding environment.
- Often requires post-weld machining or heat treating.

As opposed to the *Electron Beam Welding* process, *Laser Beam Welding* is more economical as the initial cost for setup and maintenance is comparatively less. Size of the welding components is very much restricted in the *Electron Beam Welding* process as opposed to the *Laser Beam Welding* process. However, various research has been made to find solutions to overcome this problem. The tooling in both *Laser Beam Welding* and *Electron Beam Welding* process is complex but in comparison is much more in the *Electron Beam Welding* process. Unlike the *Laser Beam Welding* process, the *Electron Beam Welding* process generates X-rays. However, the operator is protected from the X-rays by the presence of the vacuum chamber. It can be inferred that the main disadvantage of the *Electron Beam Welding* process is its cost. However, depending on the industry it is used for and its frequency of application, the incurred cost can easily be recovered very quickly.

4. Parameters of Electron Beam Welding

The *Electron Beam Welding* process is a versatile technology wherein for each joint, material and geometry, there should be several standards developed. These parameters can be classified in notably 3 categories. They are as follows.

- The parameters characteristic to the Electron Beam are *Accelerating Voltage (U_a)*, *Beam Current (I_f)*, *Focusing Current (F)*, *Depth of Penetration (H)* and *Beam Focal Diameter (d_{f0})*
- The parameters characteristic to the Welding Joint Features are *Welding Speed (v)*, *Welding Width (B)*, *Focal Distance (d_t)*, *Vacuum Pressure (P_s)* and *Preheating Temperature (T_{pr})*
- Other parameters involve *Material Type*, *Thermo-physical* and *Chemical features* of the material and *Workpiece Thickness*. These parameters do not constitute as being a part of Process Parameters.

Accelerating Voltage (U_a) in this process refers to the potential difference that accelerates charge particles, in this case electrons from the electron gun. Maxwell's equation states that 1V accelerates an electron by 1eV kinetic energy as given by Equation 5.

$$v = \sqrt{\frac{2eV}{m}} \quad (5)$$

Where, v = Charge particle non-relativistic velocity

$e = 1.6 \times 10^{-19} C$, Electron Charge

$V = 1V$, Voltage

$m = 9.1 \times 10^{-31} kg$, Electron Mass

It can be observed that with just $1V$ we are able to accelerate the speed of an electron by almost $600 km/s$. With *Accelerating Voltage* (U_a) as $150 kV$ we can accelerate the electrons present in the electron gun at approximately 76.6% the speed of light. Accelerating the charge particles is one of the most elementary requirements in producing a high energy beam to be used for welding material. For majority of the welding operations, the *Accelerating Voltage* (U_a) is kept constant, which depending on the high voltage generator and electron beam gun is set at either $60 kV$ or $150 kV$. The graph shown in Figure 4 depicts the relation of the *Accelerating Voltage* (U_a) as a function of *Beam Current* (I_f) and *Beam Focal Diameter* (d_{f0}). It can be observed here that as the *Beam Current* (I_f) increases, the rate of increase of *Beam Focal Diameter* (d_{f0}) reduces with increasing *Accelerating Voltage* (U_a). Hence, we interpret that for a more refined control on the *Beam Focal Diameter* (d_{f0}), we need to increase the *Accelerating Voltage* (U_a) with minute adjustments made to the *Beam Current* (I_f).

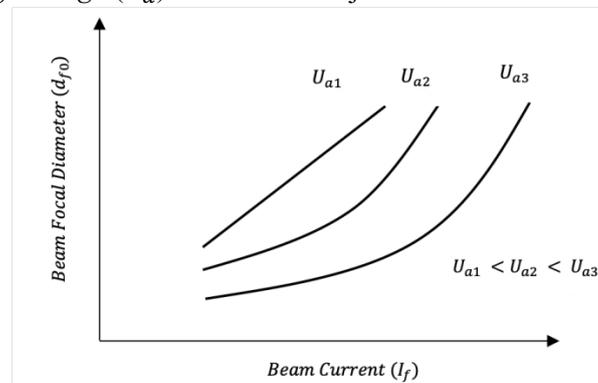


Figure 4. Beam Current (I_f) versus Beam Focal Diameter (d_{f0}) characteristics, Ref. [16]

Accelerating Voltage (U_a) also has an interesting relationship with the *Focal Distance* (d_t). *Accelerating Voltages* (U_a) of $60 kV$ and $150 kV$ are taken along with *Focal Distances* (d_t) of $350 mm$ and $1200 mm$. Figure 5 represents four experimental cases from *a-d*. The parameter configurations for these experimental cases are given by Table 2.

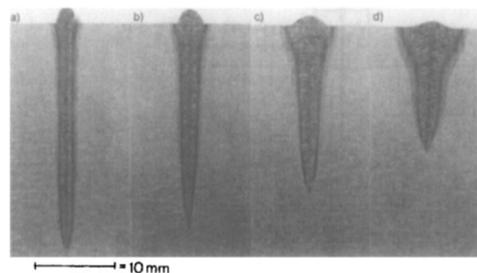


Figure 5. Depth of Penetration (H) and Welding Width (B) analysis, Ref. [16]

Table 2. Accelerating Voltage (U_a) and Focal Distance (d_t) data

Case	Accelerating Voltage (U_a), kV	Focal Distance (d_t), mm
a	150	350
b	60	350
c	150	1200
d	60	1200

Keeping the *Focal Distance* (d_t) constant and varying the *Accelerating Voltage* (U_a), it can be observed that the greater the *Accelerating Voltage* (U_a), greater the *Depth of Penetration* (H) or Fusion Zone depth. This can be inferred by comparing experimental cases *a* & *b* and cases *c* & *d*. However, if we were to keep the *Accelerating Voltage* (U_a) constant and vary the *Focal Distance* (d_t), we can observe that the greater the *Focal Distance* (d_t), wider the weld seam. Hence, the Electron Beam becomes less focused which results in a wider weld seam in the workpiece. This can be inferred by comparing experimental cases *a* & *c* and cases *b* & *d*[16]. By analyzing the surface tension of the molten metal at the weld pool, we observe that there is no risk of discharge of metal to the *Weld Root* as long as the surface tension forces are greater than the gravitational forces at the section of the weld where its width is maximum. Otherwise, the liquid metal starts to move at a higher speed from top to bottom in the vertical direction. Considering the fact that the temperature and the width of the weld pool in each successive section decrease with increase in the distance from the heat source, then at a specific moment the surface tension forces acting on the weld pool with a width $2r$ becomes equal to the gravitational force and the liquid metal stops flowing. At that specific moment, it is assumed that the radius of curvature of the root in the longitudinal direction is infinitely large. This means that the *Weld Root* will assume a nearly flat surface. This equilibrium condition can be described by Equation 6 given below.

$$\rho gh = \sigma/r \quad (6)$$

Where, ρ = Density of the liquid metal at the melting point

g = Freefall Acceleration

h = Thickness of welded metal

σ = Surface Tension coefficient

r = Radius of Curvature of *Weld Root*

Here, ρgh represents the Hydrostatic Pressure of the molten weld material. Hence, slower the *Welding Speed* (v), the rate of heat transfer to the bottom of the workpiece increases, enabling the workpiece to melt at the *Weld Joint* all the way up till the root position. If the surface tension becomes lesser than the force of gravity, the root of the *Weld Joint* will result in a depression convex surface which is undesirable as shown in Figure 6. At the same time high speed welding can result in the formation of concave depression surface in the *Weld Root* which is again undesirable due to the surface tension being greater than the force of gravity. Hence it is necessary to identify a suitable *Welding Speed* (v) range such that both melting and solidification rates are desirable as well as the surface tension forces is equal to the force of gravity at the root of the *Weld Joint* in order to produce a near flat surface.

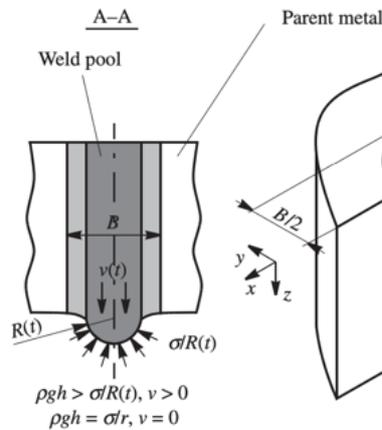


Figure 6. Hydrostatic Pressure acting on the *Weld Root* pool, Ref. [16]

In an experiment to identify the effect of *Welding Speed* (v) on the *Electron Beam Welding* process, three *Welding Speeds* (v) were chosen to identify the effect it had on the nature of the weld pool and the *Weld Root* of a 32mm Titanium Plate. They are 30m/s, 60m/s and 90m/s respectively as shown in Figure 7

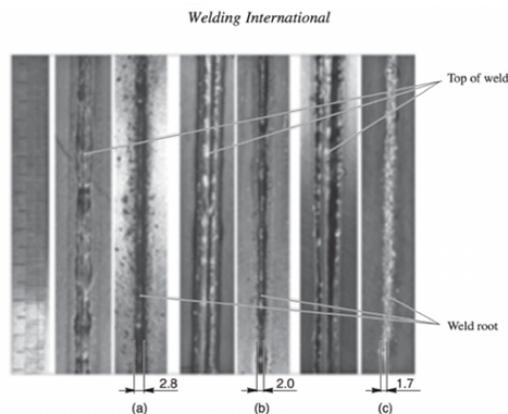


Figure 7. External appearance of the *Weld Joint* and *Weld Pool* for *Welding Speed* (v) of 30m/s, 60m/s and 90m/s, Ref. [16]

Weld Joint Analysis

It can be seen from the Figure 7 that when the *Electron Beam Welding* process was conducted at a *Welding Speed* (v) of 30m/s a large depression is observed at the tip of the weld pool and *Weld Joint*. In order to achieve a near flat surface, one would have to make a second pass with a filler wire. This is however unacceptable. At a *Welding Speed* (v) of 60m/s however, it is observed that *Weld Joint* at the tip suffers from undercutting, a variation of the large depression seen when the *Electron Beam Welding* process is conducted at a *Welding Speed* (v) of 30m/s. This can be removed by a defocused beam by means of a cosmetic pass. The need for a second pass makes this *Welding Speed* (v) not economical and hence undesirable, although it results in the desired *Weld Joint*. At a *Welding Speed* (v) of 90m/s it is observed that we obtain a *Weld Joint* without any defect, and as a result a guaranteed convexity at the tip of the weld. Hence, here the formation of the *Weld Joint* is satisfactory and can therefore be chosen as a suitable *Welding Speed* (v) for the material.

Weld Root Analysis

At a speed of 30m/s the *Electron Beam Welding* process produces a *Weld Root* of width 2.8mm . This is mainly due to persisting electron beam energy present within one section of the workpiece for a longer duration of time. This results in a higher amount of heat transfer from the top to the bottom of the workpiece than the *Electron Beam Welding* process when conducted at 60m/s and 90m/s respectively. The faster rate of heat transfer results in the elongation of the *Weld Root* at its molten phase due to the force of gravity being greater than the surface tension forces of the molten material. As a result, it can be observed that the *Weld Root* width of the *Electron Beam Welding* process when conducted at *Welding Speeds* (v) of 60m/s and 90m/s are 2mm and 1.7mm respectively. While the excess elongation of the *Weld Root* can be removed by further machining process, it is generally undesirable as it results in increased costs in the machining process of the workpiece [17].

The presence of vacuum environment in the *Electron Beam Welding* process helps prevent the accelerated and focused electron beam particles from colliding with the atmospheric particles. As we know, the weight of an electron particle is determined to be less than one ten-thousandth of a Nitrogen or Oxygen atom. As a result, when a fast-moving electron collides with an atmospheric atom it can result in the dispersion of its kinetic energy. Due to the presence of large number of atmospheric atoms colliding with fast-moving electrons, it results in the spread of the electron beam and hence in the presence of atmospheric pressure, the electron beam scatters, and is no longer focused. Figure 8 shows the effect of *Vacuum Pressure* (P_s) on the Electron Beam. 5 experimental cases were considered, where the *Vacuum Pressure* (P_s) is varied. The five different pressures analyzed are 760torr , 500torr , 250torr , 50torr and 5torr respectively. The common trend that can be observed from the figure is that with decreasing *Vacuum Pressure* (P_s), the tendency of the electron beam to scatter reduces. This is of course in-line with the need of a vacuum chamber in an Electron Beam machinery.

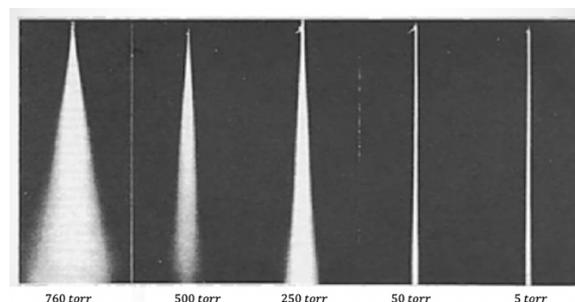


Figure 8. Effect of Vacuum on *Electron Beam Welding* process, Ref. [17]

This nature of the Electron Beam is very useful in also understanding the effect that the *Vacuum Pressure* (P_s) has on the *Depth of Penetration* (H) of the weld material. From Figure 9 it can be understood that the general trend observed is that at *High Vacuum Pressure* (P_s), the *Depth of Penetration* (H) of the electron beam in the weld material is quite high at around 90% in most cases. Whereas at *Medium Vacuum Pressure* (P_s), the *Depth of Penetration* (H) is relatively lower than that achieved at *High Vacuum Pressure* (P_s), ranging from 50% to 80% in most cases. Finally, at *Low Vacuum Pressure* (P_s), the *Depth of Penetration* (H) is the lowest and the most undesirable, as not only does its range vary from 0% to 60% but the quality of the weld penetration is poor. The *Depth of Penetration* (H) of the electron beam can also be affected by another parameter, which is the *Beam Focal Diameter* (d_{f0}).

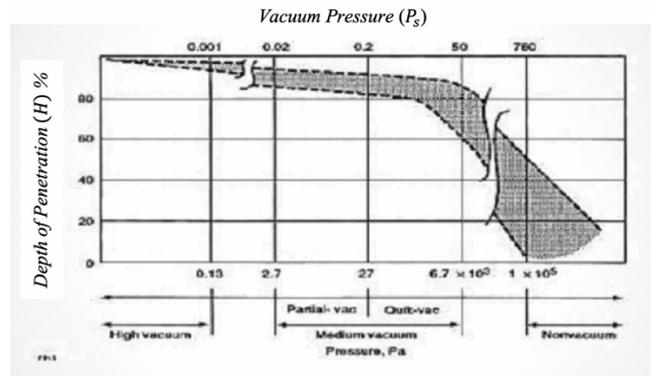


Figure 9. Depth of Penetration (H) as a function of Vacuum Pressure (P_s), Ref. [17]

The greater the *Beam Focal Diameter* (d_{f0}), lesser focused is the kinetic energy of the beam on the surface area of contact and therefore, results in reduced *Depth of Penetration* (H). However, this does not mean that the *Depth of Penetration* (H) is solely depended on the *Vacuum Pressure* (P_s). Quite the contrary. In fact, the *Vacuum Pressure* (P_s) can be said to be a disturbing factor rather than a more precise controlling factor of the *Depth of Penetration* (H). The *Depth of Penetration* (H) is an important factor that is critical for determining the quality of the *Weld Joint*. It can be given by the mathematical model as follows [18].

$$H = -144.143 + 0.137I_f - 26.346v + 0.218F \quad (7)$$

Similarly, for the *Welding Width* (B), the mathematical model is as follows.

$$B = -57.17 + 0.0135I_f - 6.731v + 0.092F \quad (8)$$

It can be observed very clearly that both the *Depth of Penetration* (H) and the *Welding Width* (B) is a function of *Beam Current* (I_f), *Focusing Current* (F) and *Welding Speed* (v).

Some materials, prior to welding, such as low-alloy steels are generally required to be preheated to a specific temperature known as the *Preheating Temperature* (T_{pr}). For any particular steel that has to be welded by any fusion welding process, the *Preheating Temperature* (T_{pr}) has been determined to be about 50°F above the *Martensite Start Temperature* (M_s). However, most low-alloy steels have fairly high *Martensite Start Temperature* (M_s), making welding uncomfortable and thus can potentially compromise the weld quality. For this specific reason, industries generally preheat such material in the order of 200-600°F below the *Martensite Start Temperature* (M_s). Most low-alloy steels that are susceptible to Hydrogen-induced cracking, transform from Austenite when cooling through the 1470-930°F temperature range. The amount of time, $\tau_{8/5}$ (seconds), a steel spends in this temperature range during cooling, will determine its microstructure and hence, its susceptibility to cold cracking. A microstructure that is free of untampered Martensite is desired to maximize cracking resistance. The Austenite therefore is transformed to ferrite + carbide so that no Austenite would be available to transform to Martensite upon reaching the *Martensite Start Temperature* (M_s).

A relationship has been formulated to establish the Critical Time, $\tau_{8/5}$, for a Martensite-free HAZ in low-carbon alloy steel. This relationship is termed as the Carbon Equivalent, CE^* and it is defined as follows [19].

$$CE^* = \%C^* + \frac{\%Mn}{3.6} + \frac{\%Ni}{9} + \frac{\%Cu}{20} + \frac{\%Cr}{5} + \frac{\%Mo}{4} \quad (9)$$

Where, $\%C^* = \%C$ for $C \leq 0.3\%$ and $\%C^* = \frac{\%C}{6} + 0.25$ for $\%C > 0.3\%$

The Critical Time, $\tau_{8/5}$, is computed from the equation as follows.

$$\log \tau_{8/5} = 2.69CE^* + 0.321 \quad (10)$$

5. Optimization Techniques of Electron Beam Welding

An experiment was designed by Ritesh Jaiswal et al. [23] based on the *Design of Experiment* techniques to examine the influence of major *Process Parameters* on the strength of the *Electron Beam Welded Joint*. To determine the optimum value of *Tensile strength* and *Microhardness* of the *Electron Beam Welded Joint* of $Fe_{49}Co_2V$ alloy and the optimum value of *Process Parameters* that helps obtain the desired optimum values, 1cu meter *Electron Beam Welding* machine of TECHMETA is used for welding specimens.

Workpiece Preparation

Cobalt-Iron alloy ($CoFe$) $Fe_{49}Co_2V$ of dimensions 150mm x 40mm x 3mm is used under the *Electron Beam Welding* specifications as shown in Table 3.

Table 3. Specification of *Electron Beam Welding* Machine

Sl. No	Elements	Description
1.	Vacuum chamber	350mm x 360mm x 400mm
2.	Chamber pumping system	Oil diffusion pump (backed by a rotary vane pump)
3.	Electron Beam gun system	Heated cathode gun (60kV) with a dedicated vacuum system
4.	Manipulation system	Vertical gun movement, the rotary manipulator (radial weld), the rotary manipulator (facial weld)
5.	Gun vacuum	$1 \times 10^{-1} \text{mbar}$
6.	Accelerating Voltage (U_a)	20kV to 60kV
7.	Beam Current (I_f)	0mA to 100mA
8.	Welding Speed (v)	0mm/min to 500mm/min

Experimental Analysis

Using *Taguchi Orthogonal Array* method from the *Design of Experiments*, a series of 9 experiments have been determined to examine the influence of the *Process Parameters* on the *Tensile Strength* and *Microhardness* of the *Electron Beam Welded Joint* of $Fe_{49}Co_2V$ alloy. This is shown in Table 4.

From Ref. [23], *Microhardness* testing on all 9 samples are done under a load of 5Kgf and the corresponding result of the *Microhardness* values are given in Table 5. Similarly, the *Tensile* tests are performed using a Universal *Tensile* testing machine and the *Tensile Strength* for all 9 samples are shown in Table 6.

Table 4. *Taguchi Orthogonal Array* with Selected *Process Parameters*

Experiment No.	Beam Current (mA)	Voltage (kV)	Welding Speed (mm/min)	Focus Current (mA)
1.	6	55	30	2435
2.	6	45	20	2210
3.	6	50	10	2365
4.	5	55	20	2365
5.	5	45	10	2435
6.	5	50	30	2210
7.	7	55	10	2210
8.	7	45	30	2365
9.	7	50	20	2435

Table 5. Test result of *Microhardness of Weld Joint*

Sl. No	Beam Current (mA)	Voltage (kV)	Welding Speed (mm/min)	Focus Current (mA)	HRC	HV
1.	6	55	30	2435	27.4	282
2.	6	45	20	2210	25.2	267.7
3.	6	50	10	2365	22.6	251.7
4.	5	55	20	2365	27.0	283.0
5.	5	45	10	2435	25.3	273.6
6.	5	50	30	2210	25.8	270.9
7.	7	55	10	2210	29.5	298
8.	7	45	30	2365	27.5	283
9.	7	50	20	2435	26	278

Table 6. Test result of *Tensile Strength of Weld Joint*

Sl. No	Beam Current (mA)	Voltage (kV)	Welding Speed (mm/min)	Focus Current (mA)	Tensile Strength ($\frac{N}{mm^2}$)
1.	6	55	30	2435	127.7
2.	6	45	20	2210	69.4
3.	6	50	10	2365	316.6
4.	5	55	20	2365	477.7
5.	5	45	10	2435	27.77
6.	5	50	30	2210	50
7.	7	55	10	2210	505.55
8.	7	45	30	2365	200
9.	7	50	20	2435	425

From Table 5 it can be clearly observed that maximum hardness HRC of 29.5 and HV of 298 is achieved with *Beam Current* (I_f) of 7mA, *Accelerating Voltage* (U_a) of 55kV, *Welding Speed* (v) of 10mm/min and *Focusing Current* (F) of 2210mA. From this we can establish that with an increase of *Beam Current* (I_f), *Microhardness* of the *Weld Joint* increases. From Table 5 it can also be determined that both *Accelerating Voltage* (U_a) and *Welding Speed* (v) play a significant role in determining the *Microhardness* of the *Weld Joint*. However, it is not clear that which of the two is a dominant factor as observed from the data of the 9 welding samples. We can still infer that with the increase of *Accelerating Voltage* (U_a) or *Welding Speed* (v), *Microhardness* will also increase. Similarly, we can also observe that the *Focusing Current* (F) is proportional to the *Microhardness* of the *Weld Joint*. In the case of *Tensile Strength*, the *Process Parameters* affect this quantity at the *Weld Joint* similar to how they do so with its *Microhardness*. Of course, this experiment is performed for the Cobalt-Iron alloy ($CoFe$) $Fe_{49}Co_2V$, but the behavior observed by the *Process Parameters* on the *Microhardness* and the *Tensile Strength* of the *Weld Joint* can be generalized for all materials welded using the *Electron Beam Welding* process. In short, in order to increase the hardness of the *Weld Joint* drastically, a significant increase in the *Beam Current* (I_f) is desired. To ensure minute increase or decrease in the *Microhardness* of the *Weld Joint*, the *Accelerating Voltage* (U_a), *Welding Speed* (v) and the *Focusing Current* (F) are adjusted accordingly.

6. Recent Trends and Innovations in Electron Beam Welding

Electron Gun

Shorter filament life, beam voltage and even current ripple, poor beam reproducibility and a tendency to gun discharge particularly when welding light alloys are various problems that are a direct result of direct heating of triode guns. Hence, the need to overcome these problems have been relentlessly

pursued by researchers across the globe. One such solution proposed was the indirect heating of diode guns. This change, from redesigning the electron gun from triode to diode helps prevent surge in current if flashover occurs. This however results in a reduced beam current. This design change reassesses both the gun and the power source approach and hence, designs a unique indirectly heated gun and switch mode power without the need for auxiliary power supplies, thus simplifying the system and overcoming the problems stated above. This also helps prevent risk of defects at high-valued components [20]. The use of RF excitations in the gun cartridge was significant in making the necessary improvements. The RF power collected by the single turn windings produces a high current in a ribbon filament. Figure 10 shows that electrons are drawn from the filament every half cycle producing a beam that then heats the main cathode. The requirement of only one cable connection to the high voltage supply so that a single core flexible cable can be employed is the innovation in this design [21].

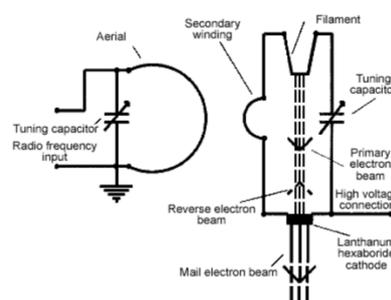


Figure 10. Circuit diagram and principles of operation of an RF excited filament and indirectly heated cathode Ref. [21]

Reduced Pressure Welding

Out of Vacuum *Electron Beam Welding* has been employed in the automotive sector for thin component manufacturing in the USA for decades. It is only in recent times that increased efforts have been made to push forth this technology. These achievements were made possible by the development of the 200kV, 100kV Electron Beam systems which could operate over the pressure range of 1000mbar to 0.01mbar, using differently pumped stages in the beam transfer column. This development has resulted in the possibility of doing away with large vacuum chambers and particularly the worry of leaks and seals. Pressure of approximately 1mbar could be achieved with simple mechanical pumps and crude local seals with the new system. C.S Punshon has described his work on optimization of vacuum conditions, weld procedure optimization, and the associated weld quality and mechanical properties [22]. His works shows us that *Reduced Pressure Electron Beam Welding* (RPEBW) process is capable of producing single pass welds in modern pipeline steels with satisfactory quality. Similarly, efforts are taken for developing the *Reduced Pressure Electron Beam Welding* (RPEBW) process for copper canister fabrication for the Swedish Nuclear Fuel and Waste Management Company (SKB), since copper used as a main corrosion barrier for nuclear waste is accepted in Sweden.

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