On the Use of High Density Electron Beams for Welding

By C AMBASANKARAN
P H RON
A K RAY
P T RAJU*

Introduction

The use of the electron beam for welding, melting and evaporating was visualised by Marcells von Pirrani as early as 1907 when he patented a workable electron beam furnace in the United States. The use of the technique in those days was however limited to small objects and slow heating rates due to electrical discharges caused by the out-gassing of the metal heated and poor vacuum conditions. These problems were solved later by providing better vacuum systems with faster pumping speeds and better voltage stabilization.

Advantages of Electron Beam Welding

The main advantages of the electron beam welding process over the conventional types are enumerated below.

(1) High power input can be concentrated into very small areas. Power densities of the order of megawatts/sq. cm. of surface area are easy to achieve with an accelerating voltage of 10-20 KV. Power densities as high as 10^8-10^9 watts/sq.cm. may be obtained with the accelerating voltage in the range 100-150 KV. With this power density, a depth to width ratio of 20 : 1 can be achieved. Table 1 gives the comparison of power densities for different types of heat sources.

* The authors are from the Technical Physics Division, Bhaba Atomic Research Centre, Trombay. This paper was presented at The Institute's Seminar held in Bombay on 31st January 1970.

Table 1

Characteristics of heat sources

	Minimum area (sq.cm.)	*Maximum power density (Watts/sq.cm.)*
Oxy-acetylene flame	10^{-2}	10^4
Electric arc	10^{-3}	10^5
Electron beam	10^{-4}	10^9

(2) One of the most important advantages of the electron beam technique is that melting or welding is carried out in high vacuum which is necessary for the electron beam. The operation is normally conducted under a pressure of 10^{-4} torr or less. Fig. 1[2] graphi-

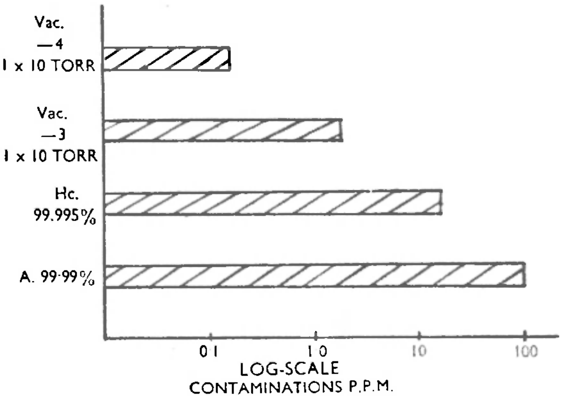

Figure 1—Comparison of the level of gas contaminants present in vacuum and inert gas atmospheres.

cally shows the level of contaminants prevailing in vacuum as opposed to inert gas atmospheres. In addition, gas impurities such as hydrogen which are evolved during the welding process are retained within the chamber instead of being evacuated immediately as in the case of electron beam welding.

(3) The beam power and the spot diameter can be readily controlled by varying the accelerating voltage, filament current and the focussing field. The beam can be deflected electromagnetically or electrostatically.

Physics of the Electron Beam Welding Process :

When electrons with high kinetic energy impinge on a target material, they are stopped and in the process give up their kinetic energy. The energy is first transferred to the lattice electrons which transmit the vibrational energy to the total lattice. The amplitude of the lattice vibration is increased which results in a rise in the temperature of the material. In fact the temperature rises so high that the material melts and even evaporates.

The shape of the fusion zone produced during electron beam welding is quite different from that produced by normal surface heating techniques where penetration is dependant upon thermal conductivity. Comprison of fusion zones shows that to penetrate a given thickness of material, only a small fraction of the material must be melted during the electron beam welding, resulting in less distortion and material property change.

It is well known that electrons of a few hundred kev can penetrate matter to only a few thousandths of an inch unless the material density differs considerably from that of the solid to liquid state. However, experience has shown that during electron beam welding, electrons penetrate materials to depths exceeding one inch. An explanation of this phenomenon in a simple step fashion given by Helmut Schwarz[3] and shown in fig. 2 is as follows. The electron beam penetrates the surface of the material to a depth of ax_m ($a<1$ and x_m is the penetration depth in the material for electrons of the given energy) without heating this layer and there inside the electrons are scattered and stopped thus heating a pear shaped volume. Intense local heating and vaporisation results in the rupture of the thin surface at the top thereby opening a channel '0' and releasing the high internal pressure. As the vapour density decreases, electron scattering becomes less and the vapour formed refocusses the beams on the first. The entire process is now repeated.

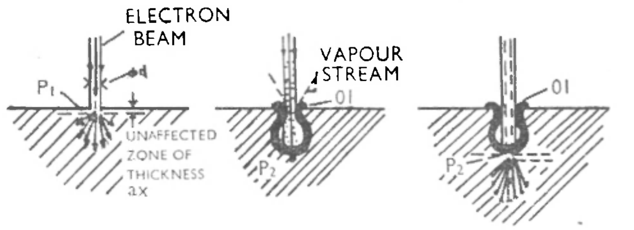

Figure 2—Step fashion representation of electron beam penetration into the materials.

When a beam is moved along a seam, the same mechanism as described above will be repeated at neighbouring spots, although the vapour probably will redeposit mainly within the previously struck channel rather than leaving the material. If a given energy density is exceeded, the forces become so high that the electron beam cuts and leaves a hole or slot rather than completing the weld. This value of energy density of course, depends on the characteristics of the material being welded.

Design Features of High Power Density Electron Beams

In fig. 3 is shown a schematic sketch of electron beam welding. The heart of the set-up is the electron gun. An electron gun is a device which generates, accelerates and to some extent focusses the beam of electrons. Broadly the electron guns can be divided into two classes (a) self accelerated gun, where the anode has a central aperture through which the beam passes and (b) work accelerated gun, where the work piece itself acts as the acclerating electrode. Here only the self accelerated gun will be discussed.

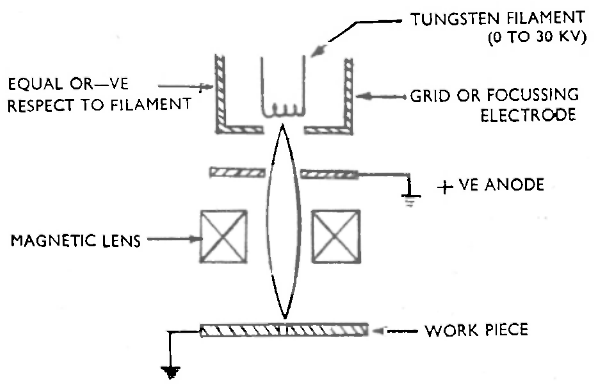

Figure 3—Schematics of electron beam welding.

Basically an electron gun is a triode. The beam is accelerated by the electrostatic field between the cathode and anode and passes through the anode aperture. The grid or focussing electrode is operated either at the same potential as that of the cathode or with a small negative bias. The grid bias controls the beam current. The required beam characteristics are obtained by a suitable design of the cathode, focussing electrode and anode structures.

The electron beam after emeging from the anode is focussed on to the target by either electrostatic or magnetic focussing.

Some considerations in the design of the electron beam system are briefly discussed below :

Cathode Material

Before discussing the gun design, one has to make the choice of cathode material. Since the cathode is the electron emitter it should be capable of giving high electron emission. At the same time it should not be susceptible to poisoning by gases like oxygen and nitrogen evolved during welding and by oil and metal vapour. For high emission current density, the cathode material must be heated to high temperatures i.e. above 2000°C and so the choice falls among the refractory materials with low work function like rhenium, tantalum and tungsten.

The refractory metal cathode is heated either by the direct passage of current or by electron bombardment from another filament. The most common cathode used in welding is that of tungsten wire wound in the form of flat spiral or helix, heated by the direct passage of current. This type of cathode however has the inherent limitation that the spot is not so well focussed as in the case of a unipotential shaped cathode. When the filament type cathode is operated at very high temperature, it will have a tendency to sag slightly and thus will become non planar. Since the trajectories of the electrons are very sensitive to small changes in cathode shape, this is a major source of trouble.

An arrangement which avoids the defects of the wire wound filament is obtained by an indirectly heated cathode, where a tantalum cathode is heated by electron bombardment. This type of unipotential shaped cathode has some remarkable advantages of producing a fine focussed beam ; also the life of the cathode may be increased by using a larger surface area and operating at lower current density.

The properties of some of the cathode materials are given in table 2. Although the tantalum has better emission characteristics compared to tungsten, for filaments in the form of spirals or helices its resistance to sagging is low and hence tungsten is generally preferred. For cathodes in the form of shaped discs however, tantalum is used because of its better machinability.

Table 2

Cathode	*Emission/cm²*	*Operating temperature°C*	*Work Function eV*	*Upper pressure limit for operation torr—*
Tungsten	0.6	2200	4.55	10^{-4}
Tantalum	0.5	2200	4.1	10^{-5}
Rhenium	0.2	2200	4.8	10^{-4}

Electron Gun Design

After the specification of the cathode material, the design of the electron gun is carried out to meet the energy and the current requirements of the electron beam. The choice of the beam energy and current will be guided by the type of use to which the system is put.

The type of beam preferred for welding is a cylindrical columnar beam which can be focussed to a very small spot size. This type of beam may be obtained using Pierce type electron gun (5,6). When properly designed, the minimum beam diameter lies well beyond the anode, and thereafter the beam diverges uniformly. The fundamental advantage of the Pierce gun is its design ease along with its high efficiency. With proper care efficiency may go as high as 99.9%, which means only about 0.1% of the beam current is lost to the electrodes. Beyond the minimum beam diameter after the anode, the beam diverges due to the space charge effect. This necessitates the use of auxiliary focussing to counteract the beam spread. The work piece is kept about 8-12 inches away from the gun to protect it from any possible arcing due to degassing.

Focussing Lens

The focussing may be of electrostatic or electromagnetic type. Electrostatic lenses are usually avoided because of the necessity of a variable high voltage supply and the consequent insulation problems. Also any degassing of the work piece may cause the high voltage electrostatic lens to arc, thus putting off the focussing action. The magnetic lenses do not have these troubles, hence normally magnetic lenses are used.

A 6K.W. Electron Beam Welding Unit

A 6KW welding unit has been designed and fabricated in the Technical Physics Division of Bhabha

Atomic Research Centre and has been successfully used for welding a variety of materials. Among the materials welded in sheet and tube form are stainless steel, tantalum, kovar, copper and zircaloy. The assembly of various parts of the furnace is shown in Fig. 4. The unit consists of an electron gun, a vacuum system and the associated power supplies. In the electron gun (Fig. 5) the cathode is of directly heated type, made of 20 mil. tungsten wire wound in the form of helix of 3 turns. The filament heating transformer insulated for the accelerating high voltage, was designed to give 375 watts power.

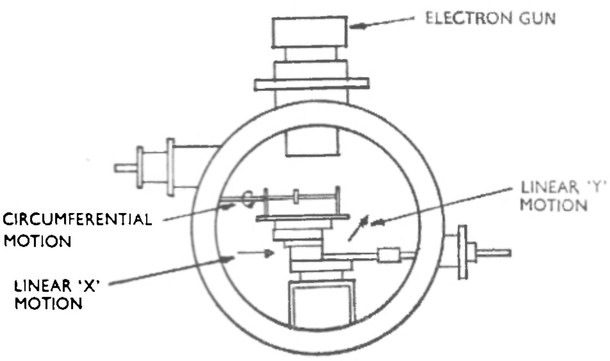

Figure 4—Assembly of vacuum chamber and electron gun.

Vacuum System

The vacuum chamber is a stainless steel cylinder of $\frac{1}{4}''$ wall thickness, the depth being 12″ and the diameter 24″. The chamber has six side ports and the electron gun is mounted on one of them. The magnetic lens sits between the chamber and the electron gun. The magnetic lens is of the short type coil wound on a brass former. The lens coil is designed to give a focal length of 1″ at 30 KV accelerating voltage. The ampere turns required to give the focal length is calculated from the formula

$$IN = 220F_c \left(\frac{V_k d}{f}\right)^{\frac{1}{2}}$$

where I = current in amperes flowing through the coil
N = number of turns of the winding
d = mean diameter in centimetres of the winding
V_k = voltage expressed in kilo volts
f = focal length in centimetres
F_c = coil factor (between 1.1 and 1.2 for unshielded coils).

The winding has 500 turns and can carry upto 5 amps.

Inside the chamber is housed a work table on which the job to be welded is held. It can be moved in two perpendicular directions x and y. Two variable speed motors mounted outside the chamber, are coupled to two drive shafts through reduction gear, pulley and belt arrangement. The drive shafts are led into the vacuum chamber through Wilson type vacuum seals. Inside the chamber, these shafts are connected to the work table through universal joints and lead screw arrangements. The lead screws convert the rotational motion of the shafts into the linear motion of the work table. The universal joints facilitate simultaneous motion of the table x and y directions. The facility for circumferential welding round a horizontal axis is also incorporated. A third variable speed motor gives the necessary drive to the job.

The vacuum chamber is evacuated by a three stage oil diffusion pump having an unbaffled speed of 2000 lit/sec, backed by a two stage rotary pump with a pumping speed of 450 lit/min. The baffle valve provided with the diffusion pump reduces to a great extent back streaming of oil vapour. With this pumping system, a high vacuum of 2×10^{-5} torr is obtained in 30 mts. However during welding the excessive degassing of the work piece may cause pressure rise in the vacuum chamber. If the pressure rises above about 5×10^{-3} torr a high voltage arc discharge will occur and the protecting relay will operate to trip off the high voltage power supply. This protects against any weld being made under conditions of poor vacuum. The pressure inside is monitored by a Penning type cold cathode ionization gauge. The backing pressure is measured by a thermocouple gauge.

High Voltage Supply

The high voltage power supply can give a continuously variable d.c. voltage upto 30 kv and has a current capacity of 200 ma. The d.c. voltage is obtained by a conventional voltage doubler circuit using high voltage rectifiers and condensers. A single phase transformer which has a voltage step up ratio of 1 : 60 feeds the voltage doubler circuit. The rectifiers are protected by over load relays. The electronic unit also houses the control circuits for the vacuum gauges and d.c. power supply for magnetic lens.

Application of Electron Beam Welding

A high vacuum electron beam welding unit is an extremely useful tool in advanced technologies. Its unique advantages are—(a) the high heat concentration which produces a narrow heat affected zone, (b) pro-

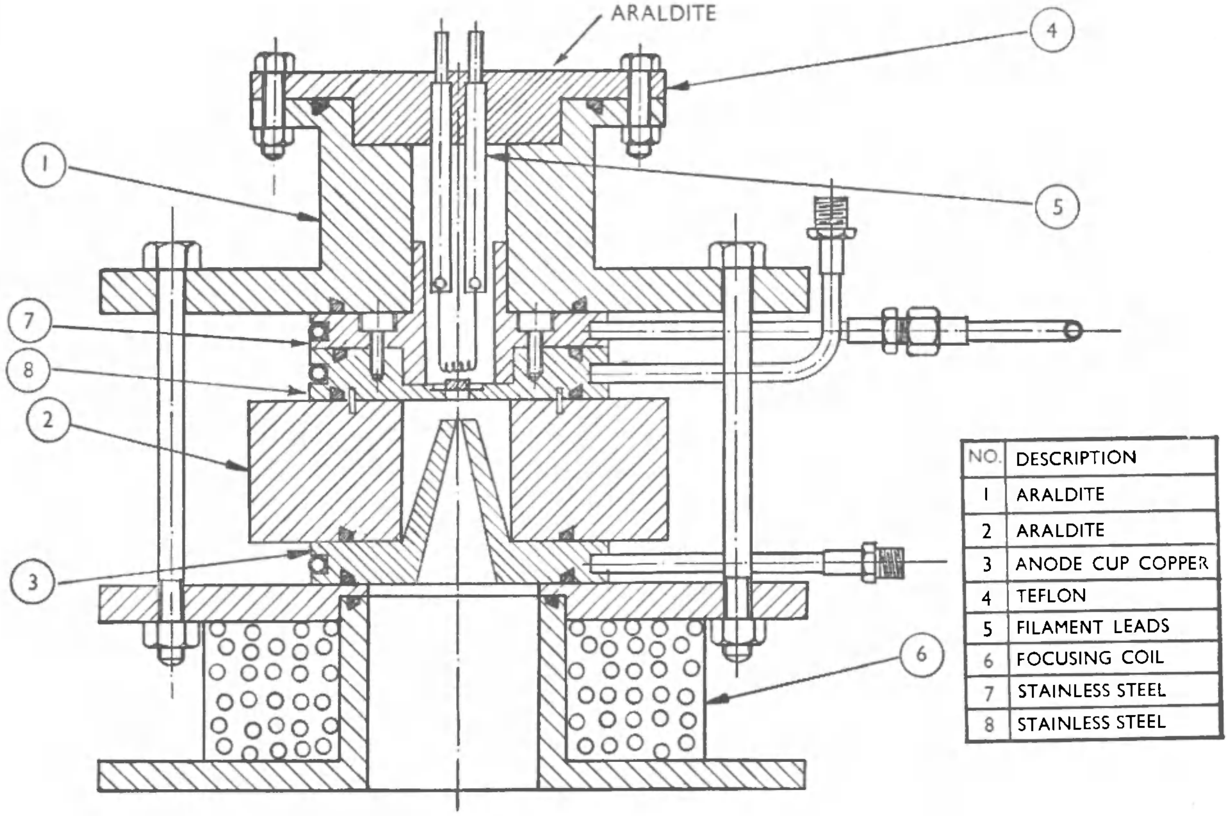

Figure 5—Electron gun assembly.

duction of extremely high purity welds which are essential for nuclear reactor assembly fabrication and (c) high depth to width ratio of the weld. However, restrictions are imposed on the job size and its manoeuverability by the vacuum chamber.

Electron beam welding under protecting gas at atmospheric pressure is assuming increasing importance in welding technique (Fig. 6). Here the high energy electron beam is produced by an electron gun and focussing system in a high vacuum of 10^{-5} torr. The beam is then allowed to pass through successive chambers at higher pressures and ultimately to a region of atmospheric pressure of Argon. The weld properties are similar to those of vacuum electron beam welding. Since welding is carried out outside the vacuum chamber one can weld work pieces of any desired size and particularly continuous fed weld e.g. long cables. The atmospheric type of electron beam welder is also very suitable for production type of welding work as the recycling operation, normally present in the vacuum welder, is eliminated. Due to strong scattering of electron beam by the surrounding gas the attainable depth of width ratio of the welding spot is limited to 5 : 1.

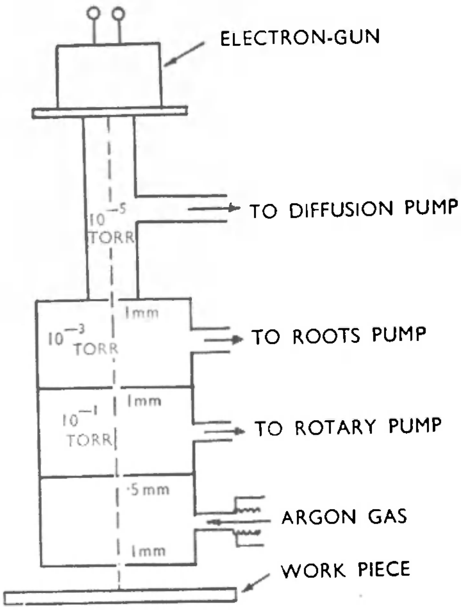

Figure 6—Schematic diagram of atmospheric electron beam welder.

The Technical Physics Division of Bhabha Atomic Research Centre has taken up the development of an atmospheric electron beam welder.

Acknowledgement

The authors wish to acknowledge the full time assistance of Shri A. S. Fernandes and the help of Shri V. Ramaswamy in designing mechanical parts. Thanks are also due to Shri S. K. Iyyengar and Shri C. K. Shah for many helpful discussions.

References

(1) Proceedings of the Second Symposium on Electron Beam Melting (Alloyed Corporation), 24-25 March 1960.

(2) Haffman. H. H., "Vacuum joining by electron beam welding" Transactions of the vacuum metallurgy Conference, 1960 pp. 255-87.

(3) Helmut Schwarz. "Electron beam processes at different voltages", Vacuum Symposium Transactions (1961) Vol. II, pp. 699-707.

(4) Smullin, L. D., "Some elementary considerations in the design of electron beam for welding and heating", proceedings of the Third Symposium on Electron Beam Technology, 23, 24 March 1961, pp. 8-25.

(5) Davidson, W. E., Rosenfeld, J. L. & Saloom, J. A. "A detailed analysis of beam formation with electron guns of Pierce type". Bell Syst. Tech. J., 35 (1956), 375-420.

(6) Pierce, J. R., "Rectilinear flow in beams", J. appl. Phys., 11 (1940). 548-54.

ERRATA

In the May 1970 issue of Indian Welding Journal, the name of the author of the paper 'Welding Metallurgy of Stainless Steels' has been shown in pages 57 and 70 as *Dr.* P S Subba Rao. The author has pointed out that he is working for his Ph.D. but does not have as yet a doctorate.

Mr S K Mazumdar of Bharat Heavy Electricals Ltd., Tiruchirapalli has drawn our attention to some errors in the list of members published in the May 1970 issue of IWJ. The names of Messrs. V Sundararajan (OM), J T Dorairaj (AM) and T N Shanmugaraj (AM) had been incorrectly spelt and that of Mr P S Sundararajan (AM) omitted from the list. Mr H L Shukla (AM) is from Heavy Electricals. Bhopal and not from B H E L, Tiruchirapalli. Mr R Krishnan is an Associate and not a student member.

Our apologies to all those to whom embarrassment has been caused by these errors.

Editor
IWJ.