Electron Beam Welding: study of process capability and limitations towards development of nuclear components

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Abstract. Electron Beam Welding (EBW) technology is an established and widely adopted technique in nuclear research and development area. Electron beam welding was thought of as a candidate process for ITER Vacuum Vessel Fabrication. Dhruva Reactor @ BARC, Mumbai and Niobium superconducting accelerator cavity @ BARC has adopted the EB welding technique as a fabrication route. Study of process capability and limitations based on available literature is consolidated in this short review paper.

1. Introduction

EBW (Electron Beam Welding) equipment covers a range of power from 2 to 200 kW. Using vacuum chambers ranging from few litres to several hundred cubic meters have ensured a production rate of few parts per day (aircraft structures, heavy industry and the petrochemical industry) to more than a thousand parts per hour (automobile) [2]. The application of EB welding for the strategic use is reported. In France, in the 1980s, a big machine of 264 m³ (with an internal gun of 45 kW) was used for welding internal core barrels for the nuclear industry. Later, even bigger chamber of 800 m³ was realized by Technéos in France for welding submarine components [2]. EBW machine at NAMRC (Nuclear Advance Manufacturing Research Centre) has the vacuum chamber volume over 200 m³ and beam power 30 kW (at 60kV), which is capable to make full penetration single-sided welds of 100 mm thickness in steel. A few examples of large EB welding installations for other purposes include a machine at Nates (France) having chamber size of 860 m³ volume (diameter 10 m and length is 11 m) [1] and a machine at Kazan Aircraft Production Association in Russia having total length of the chamber 38 m and the total volume of the vacuum chamber 1160 m³ with beam power 120 kW at 120 kV [2]. Internationally as per 1979 estimate there are more than 3000 installations of EBW machines [3]. A survey of EBW & its capabilities is compiled in this short review paper.

Figure 1 shows current state of experience and information regarding material combinations and their welding compatibility for EBW.
Figure 1. Current state of experience and information regarding material combinations and their welding compatibility [4].

2. EB Process Parameter
The output parameter of EBW, such as the depth of penetration, thickness of the thermal affected area, productivity, working time, surface precision etc. depend on input parameter [9]. A few important EB welding parameters are listed below.

- Vacuum parameter: vacuum in EB gun, vacuum in working chamber.
- Work piece material parameter: melting temperature and thermal conductivity of work piece.
- Electron beam parameter: electron beam diameter, electron beam power, beam current, beam current intensity, acceleration voltage.
- Beam focus parameter: form, amplitude and frequency of oscillation, focalisation current, focal point and beam oscillation, focal distance.
Other parameters like welding distance, welding speed.

Some of the EB gun configurations commercially available (or were available) are shown in figure 2.

**Figure 2.** Partial list of commercially available electron beam gun configurations (left – moving EB gun [6], middle – EB gun for out of vacuum [5], right – EB gun for welding tubes in to heat exchanger using local vacuum [2].

3. **EB capabilities**
A few examples of various types of welded joints produced by EBW are shown in figure 3 and figure 4.

**Figure 3.** Examples of components produced by EBW, (a) Thick to Thin Welding [2, 10], and (b) Horizontally weld aluminum, penetration depth: 150 mm [12], (c) 45 mm deep weld seam in SS [10], (d) Bronze/Steel material welding of 30 mm [10].
Electron beam welding experience (of a job shop) according to material can be summarized as below [10].

- In practice, most of steel materials are weldable by means of an Electron Beam without any special requirement such as pre-heating or using filler wire. 0.1 mm to 200 mm structural steel can be welded.
- Low alloyed steels as e.g. fine grained steels, case hardening or nitriding steels (for welding the case has to be removed or not applied in the welding zone), as well as steels for high temperature service, construction steels and most heat treatable steels are readily EB weldable.
- Most of the stainless and acid resistant steels, such as austenitic, ferritic or duplex steels are readily EB weldable. 0.5 mm to 45 mm thick components can be welded.
- Wrought aluminium alloys, either forged or extruded are usually readily weldable. 50 mm to 200 mm thick Aluminum can be welded.
- Magnesium Alloys containing 6% to 9% of aluminium and up to 1% of zinc, are readily weldable.
- SE, SF and OFHC copper are readily weldable. There are more than 1000 EB welded clamps of Cu Be 2 in the ASDEX fusion reactor.
- Pure nickel and pure cobalt as well as many of their alloys like Ni Mn 2, Ni Cr 80 20, Ni Cu 30 Fe are readily EB weldable.
- Reactive materials like titanium, zirconium, tantalum, vanadium or niobium exhibit a strong affinity to oxygen and hydrogen, especially at elevated temperatures. EB welding under vacuum provide the ideal environment for these materials.
- In principle, it is possible to EB weld any dissimilar metals to each other, even if their melting points are far apart, those metals, which alloy easily with each other are EB weldable without problems. Welding austenitic to martensitic steel, steel to bronze and many practical examples are mentioned in [10].

All electron-beam-welded wing carry-through structure of the F-14 Tomcat (very advanced fighter plane) was arguably one of the most sophisticated weldments ever put into production [11]. TWI has also reported the full penetration, 60 mm thickness, 1300 mm long seam weld 2350 mm diameter S355 steel using mobile electron beam welding concept [5].

4. Limitations of the technology

The introduction of a new technology almost invariably leads to exaggerated claims about its capabilities from over-zealous promoters of its virtues. The multi-functional electron beam welding process that has evolved over the past 50 years has definitely proved to be an extremely powerful welding tool when applied within the confines set by normal physical metallurgy and metallurgical thermodynamic limitations [2].
Electron beam welds are not immune to the same type of defects as shown in figure 5 (e.g. porosity, spatter, shrinkage, cold shuts, cracking, etc.) [2].

5. Conclusion
From the survey, it is realized that EBW is a useful technology for joining of similar or dissimilar materials with a variety of material thicknesses. It has a wide range of application in industrial as well as in research field.

The knowledge gained at various Institutes in India like BARC (Bhabha Atomic Research Centre), RRCAT (Raja Ramanna Centre for Advanced Technology), IUAC (Inter University Accelerator Centre), ISRO (Indian Space Research Organisation) and BHEL (Bharat Heavy Electricals Limited) in the area of EB welding needs to be consolidated for a national level facility for nuclear / strategic application. Suitability of out of vacuum process needs to be explored in detail for large sized nuclear components.

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