Chapter 4

Design of Process Chamber for Electron Beam Melting and Welding Applications

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Electron Beam (EB) for material processing includes the application in welding, melting, refining, and evaporation processes. The EB process is carried out in vacuum and therefore, is found to be the most suitable processes involving reactive materials such as Niobium, Tantalum, Zirconium, Uranium etc. The EB is also capable of melting and vaporizing metals and alloys with high melting points such as Tungsten, Molybdenum etc. as it can be focused to very focal spot diameter to obtain incident beam power density in the range of 10^4-10^6 W/cm^2. The process chamber for EB thermal applications defines the controlled environment for the interaction of highly focused EB with the materials being welded, melted, refined or evaporated. The process chamber is connected to various sub-systems through various ports and nozzles provided on its wall. The heat load on various sub-systems defines the requirement of cooling water during the EB process. The design requirement of the process chamber for EB welding, melting, refining, and evaporation processes is discussed here. The mechanical design of a typical process chamber for EB Melting machine of 10 kW power rating is also presented.

4.1 Major Sub-systems of EB Process Equipment

The EB process chamber basically consists of a vacuum chamber with various sub-systems integrated to it via different size ports and nozzles. Figure 4.1 shows the conceptual layout of equipment used for EB processing of materials. It consists of EB Gun column, process chamber, crucible assembly, charge feeder system, ingot withdrawal system, vacuum system, cooling water system, viewing system, power supply and controls. The various sub-systems are integrated to the main process chamber to carry out EB melting, welding or evaporation process. The presence of major sub-systems in EB melting, welding and evaporation application depends on the end use and general guideline is given in Table 4.1.

Table 4.1: Major sub-systems of an EB Machine.

Sr. No.	**Sub-systems**	**EB Welding**	**EB Melting/Evaporation**
1.	EB Gun Column	√	√
2.	Process Chamber	√	√
3.	X-Y and Rotary Table	√	×
4.	Crucible Assembly	×	√
5.	Crucible Indexing	×	√
6.	Charge Feeder	×	√
7.	Ingot Withdrawal	×	√
8.	Coating System	×	√
9.	Vacuum System	√	√
10.	Viewing System	Double Glass	Stroboscope
11.	Cooling Water System	×	√
12.	Power Supply and Controls	√	√

4.2 Design Basis for Process Chamber of EB Machines

Process chamber of EB machine requires proper design for cooling, X-ray shielding and view ports. The shape of the process chamber too will be discussed here.

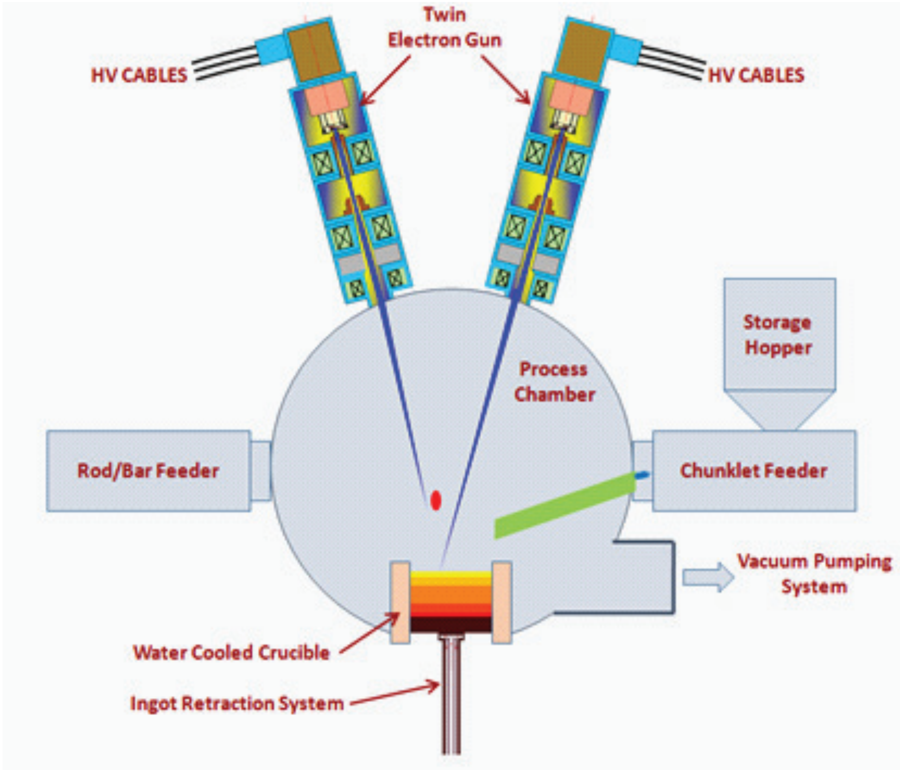

Figure 4.1: Conceptual layout of an Electron Beam Melting machine.

4.2.1 Cooling Water

The mechanical design basis for the process chamber is defined by the process condition and end application. The optimization of the process parameter in EB Welding application is carried out to obtain maximum depth of penetration with minimum fusion zone area. Therefore, the amount of molten metal involved in EB welding is very low. Moreover, the process chamber size is large with respect to the weld size due to the presence of X-Y table and rotary table in the vacuum chamber to handle different size of the jobs to be welded. Therefore, the thermal load due to molten metal and outgassing load due to release of the dissolved gases is very low. Hence, the process chamber is generally not provided with water cooling arrangement in EB welding process chamber. The accelerating voltage in the range of 15 kV to 40 kV is required for EB melting and evaporation application as depth of penetration is not the criteria [7, 10, 13]. The process chamber required for EB melting, refining and evaporation application involves a large amount of metal in the molten state during the process which results in the generation of metal vapours and outgassing of large amount of dissolved gases. Therefore, the process chamber inner walls are protected from hot spots by providing heat shields. The heat shields are thin sheets in single or multiple layers made out of Mo sheet, Inconel sheets or SS310 sheets depending upon the design requirements. The walls of the process chamber are also provided with water cooling arrangement to maintain the process chamber temperature within safe limits.

4.2.2 Lead Shielding

EB Welding is carried out at high accelerating voltage to obtain high aspect ratio i.e. weld depth to weld width ratio which necessitates it to provide lead shielding and double glass viewing arrangements to prevent the escape of any radiations during [7] if the operating accelerating voltage is greater than 60 kV. If the operating accelerating voltage is less than 60 kV, the chamber wall thickness is adequate to prevent the escape of any radiations. The process chamber walls of EB machine for melting and evaporation applications are generally not provided with lead shielding as the operating accelerating voltage is in the range of 15 kV to 40 kV.

4.2.3 View Port

View ports are provided to facilitate the operator to view inside the process chamber during the welding or melting process. The amount of metal in molten state during the EB welding is very less and the presence of metal vapours and dissolved gases released during welding is not significant to make the viewing system opaque very frequently. Therefore, EB welding process chamber viewing system is provided with double glass arrangement with implosion/explosion proof toughened glass on the inner side and lead glass on the outer side to prevent escape of any radiations. In case of EB melting and evaporation application, lot of metal vapours and dissolved gases are released which make the viewing glass opaque in one or two cycles of operation. Therefore, stroboscopic viewing ports are provided here for viewing the internals during the melting process.

4.2.4 Shape of the Process Chamber

The shape and size of the process chamber is based on criteria of optimum utilization of inner space by various sub-systems, material required for the fabrication, cooling water requirement and overall weight of the equipment. The EB welding process chamber and small process chamber of EB melter with single EB Gun are generally designed as rectangular chamber whereas large EB Melters with multiple EB guns, charge feeder, crucible or retraction system of large size ingot is generally made up of circular cross section. The process chamber wall thickness and hence the material requirement reduces approximately by 20% to 30% if cylindrical shape is chosen over rectangular shape. The EB welding machines are required to house X-Y tables, rotary tables, job to be welded and job maneuvering inside the process chamber which necessitates for opting the rectangular cross section of the process chamber.

4.2.5 Operating Conditions

The operating condition for both the EB welding and melting process chamber is high vacuum but additional design external pressure on inner wall of the process chamber is considered due to the cooling water pressure in case of melting. The design internal pressure of 3 kg/cm^2 is also considered for the large process chambers used for melting and evaporation application as cooling water pipe lines are present inside the process chamber and any failure or rupture of cooling water lines may result in the molten metal and water interaction leading to increase in momentary pressure. Table 4.2 gives the design basis of process chamber for EB applications. The mechanical design, fabrication and testing of the process chamber is carried out as per the guidelines given in ASME Boiler and Pressure Vessel Code Section VIII Division 1. Following sections illustrate the design procedure for a typical process chamber used for EB melting applications.

Table 4.2: Design basis for the process chamber of an EB Machine.

Sr. No.	Particulars	EB Welding	EB Melting/ Evaporation	Basis
1	Working pressure	High Vacuum	High Vacuum	EB welding and melting process demands high vacuum
2	Working pressure (external for inner wall and internal for outer wall)	0.01 kg/mm^2	0.01-0.05 kg/mm^2	The maximum head generated by cooling water pumps in case of water-cooled wall
3	Working temperature	80 °C	80 °C	Heat shields limits the inner wall temperature to be less than 80 °C
4	Design pressure (internal for inner wall)	Not applicable	Not applicable	For small process chamber using low power melting
			0.03 kg/mm^2	For large process chamber using high power melting, momentary exposure to high pressure due to water leakage in process chamber
5	Design pressure (external for inner wall)	0.01 kg/mm^2	0.02-0.06 kg/mm^2	Total pressure difference across the wall
6	Design pressure (internal for outer wall)	Not applicable	0.01-0.05 kg/mm^2	Cooling water pressure
7	Design Temperature	100 °C	100 °C	Operating temperature with some margin
8	Hydro-test Pressure	Not applicable	0.039 kg/mm^2	1.3 times the design internal pressure
9	Material of construction AISI 304 L SA 240 (for Shell) SA 312 (for Nozzles) SA 182 F (for Flanges)	Yes	Yes	Material selection is based on Good vacuum compatibility Good corrosion resistance Good weldability Easy availability

4.3 Design of Process Chamber for 10 kW EB Melter

The 10 kW, 15 kV EB melting machine is developed for the processing of reactive metals and alloys and production of button mould, finger mould and small cylindrical ingots of these metals and alloys. The alloys are developed in the 10 kW EB melter for the purpose of carrying out metallurgical studies. The EB melter with stationary crucible assembly for the production of buttons of 25 mm (diameter) x 15 mm (thick) and finger mould of 40 mm (long) x 25 mm (wide) x 15 mm (thick) is developed in phase-I of the project. The charge is prefilled in the cavity of the stationary crucible before start of the melting operation and melting and alloy production is carried out using EB as the heat source. There are three circular cavities for button mould and one linear cavity for finger mould in the stationary crucible assembly of 10 kW EB melter. The crucible is said to be stationary crucible as it is not provided with any motion during melting process. Once the melting is complete in one cavity, the crucible is move forward or reverse to align the next cavity with the incident EB. The cavity under consideration is aligned with EB by moving the crucible assembly using linear motion system. The linear motion of the crucible is achieved using stepper motor and ball screw arrangement. The linear motion system of the crucible assembly is placed outside the vacuum boundary via suitable vacuum seals assembly which not only enables the use of normal stepper motor but also saves the inner working space of the process chamber. The online charge feeder assembly for feeding the raw material during melting process and ingot crucible assembly along with ingot retraction system will be designed, fabricated and integrated with process chamber in phase-II of the project. Following are the major sub-systems of the EB melter system under consideration:

- EB Gun column as a heat source
- Process chamber
- Stationary crucible for making buttons and finger moulds
- Online Charge feeder (phase-2)
- Ingot Crucible (phase-2)
- Ingot retraction system (phase-2)
- Vacuum pumping system
- Viewing system consisting of stroboscopic arrangement
- Cooling water system

The number and size of various subsystems connected to the process chamber decides its size and the number of ports required on its different walls. A double walled water cooled rectangular process chamber with inner working space of 450 mm x 460 mm x 440 mm is considered for the 10 kW EB melter. Table 4.3 gives the details of various ports provided on different walls of the process chamber.

4.3.1 General Design Features

The EB melter system can be described as a high vacuum clean environment system. The base and operating pressures of the system will be in the range of 5×10^{-6} mbar. General design features of the 10 kW EB melter process chamber is as given in Table 4.4.

Table 4.3: Ports and Nozzles provided on the Process Chamber.

Sr. No.	Port/Nozzle	Size	Location	Purpose
1	N1	DN63	Top Wall	EB Gun Column mounting
2	N2	DN160	RHS Wall	For Stationary crucible
3	N3	DN100	LHS Wall	For Online charge feeder assembly
4	N4	DN160	Bottom wall	For ingot crucible
5	N5	DN160	Back side wall	For diffusion pump
6	N6	DN63	Front Door	For viewport
7	N7-N8	DN50	Back side wall	Vacuum Gauge heads and diagnostics
8	N9-N11	DN50	Back side	Shutter assembly and diagnostics
9	N12-N17	$\frac{1}{2}''$ BSP	Door, Bottom wall, and Back wall	For Cooling water connections

Table 4.4: Design features of the process chamber of 10 kW EB Melter.

Sr. No.	**Particulars**	**Value**
1.	Working condition	Vacuum
2.	Working vacuum level	5×10^{-5} mbar
3.	Cooling water pressure for water cooled components	1.5 kg/cm^2
4.	Design External pressure for process chamber inner wall, P_e	2.5 kg/cm^2
5.	Design Internal pressure for process chamber outer wall, P_i	1.5 kg/cm^2
6.	Design Temperature, T_d	100 °C
7.	Gasket material in process chamber	Viton
8.	Process chamber material	SA 240 304L
9.	Flange material	SA 182F 304L
10.	Nozzle material	SA312 TP 304L
11.	Maximum allowable cooling water pressure drop	1 kg/cm^2
12.	Maximum allowable cooling water temperature rise	4 °C to 5 °C

4.3.2 Codes and Standards

The following codes in their latest edition, including addenda shall form the basis for design, material specifications, fabrication, inspection, testing and acceptance of an equipment.

a) ASME Boiler & Pressure Vessel Code Sec. II, Part D.

b) ASME Boiler & Pressure Vessel Code Sec. VIII Div. 1 and 2.

c) ASME Boiler & Pressure Vessel Code Sec. V.

d) ASME Boiler & Pressure Vessel Code Sec. IX.

4.3.3 Mechanical Design

The process chamber of rectangular cross-section is provided with water cooling arrangement. The inner working space of 450 mm (height) x 460 mm (width) x 440 mm (deep) is maintained at a vacuum level of 5×10^{-5} mbar. It is fully accessible from the flat front door mounted on hinged support. Figure 4.2(a) shows the cross-sectional view of the process chamber and Fig. 4.2(b) shows the photograph of the process chamber during fabrication stage. The strength calculations for inner wall of the process chamber as per ASME Section VIII Division 1, Appendix 13 are given in the following sections.

Design of Unreinforced Vessels of Rectangular Cross-section (as per Appendix 13, Article 13-14, Section VIII, Division 1)

Inner wall of the process chamber is subjected to external pressure due to the combined effect of vacuum and cooling water pressure. Figure 4.3 is the sketch taken from ASME Section VIII Division 1, Appendix 13 and shows the section of an unreinforced vessel of rectangular cross-section under external pressure [14].

Factor for Unreinforced Pressure Vessel, K_3

A = $(6\phi^2\ \alpha_3 - 3\pi\phi^2 + 6\phi^2 + \alpha_3^3 + 3\alpha_3^2)$

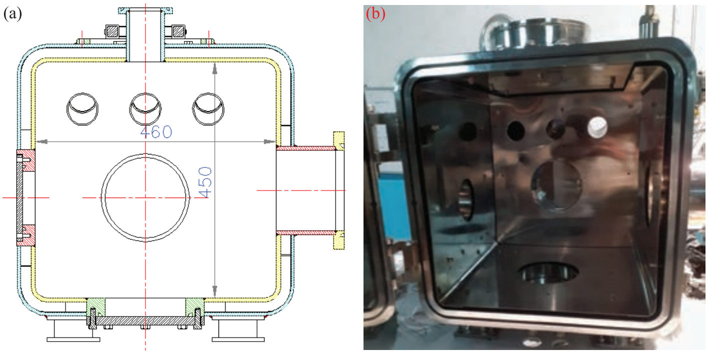

Figure 4.2: (a) Cross sectional view of the process chamber, and (b) photo of the process chamber during fabrication stage.

Design parameters

Design External pressure, kg/mm^2	$P_e = 0.025$
Allowable stress of the material, kg/mm^2	$S_a = 11.64$
Yield strength of the material, kg/mm^2	$S_y = 17.4$
Modulus of Elasticity, kg/mm^2	$E = 18976$
Poisons ratio	$n = 0.3$

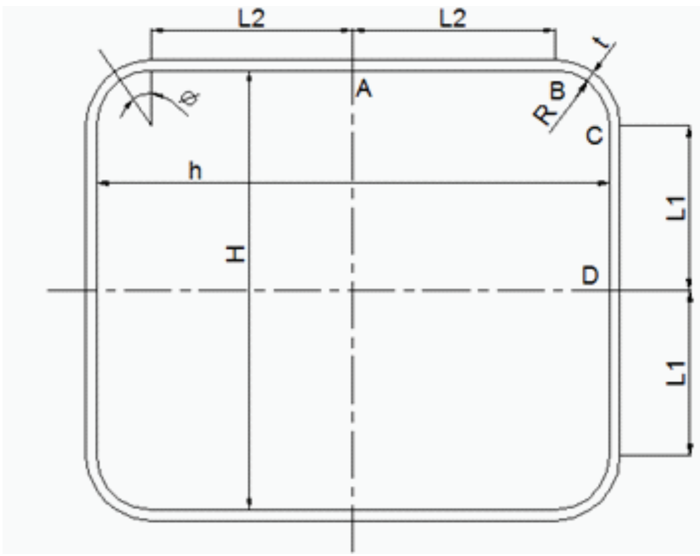

Figure 4.3: Unreinforced Vessel of Rectangular cross-section under external pressure (Fig. 13-2(a) sketch 3, App. 13, Article 13-14, ASME Section VIII Divn. 1).

$B = (- 6\phi - 2 + 1.5\pi\ \phi\ \alpha_3^2 + 6\phi\ \alpha_3)$
$K_3 = -\ L_1^2\ (A + B)[3\ (2\alpha_3 + \pi\ \phi + 2)]^{-1} = -8.791 \times 10^3$
Bending Moment at midpoint of Long side, kN.m: $M_A = P_e K_3 = -219.79$
Maximum Bending Moment at $[\theta = \tan^{-1}(L_1/L_2)]$, kN.m:
$M_r = M_A + P_e[R\{L_2 \cos\theta - L_1(1\text{-}\sin\theta)\} + L_2^2/2] = 369.22$

Dimensions of the inner wall of the vacuum chamber

Provided thickness of the vessel, mm	t = 12
Half length of the longer side, mm	$L_2 = 208$
Half length of the shorter side, mm	$L_1 = 203$
Corner radius, mm	R = 22
Length of the vessel, mm	$L_v = 440$
Provided thickness of the end closure, L_v	$t_e = 16$

As per App. 13-7 (c) Vessel per Figure 13-2(a) sketch 3

Moment of inertia of strip thickness t,	$I_1 = t^3/12 = 144$
Distance of extreme fibre from N.A., mm	$C_0 = t/2 = 6.0$
Factor, ($\phi = R/L_1$)	$\phi = 0.108374$
Factor, ($\alpha_3 = L_2/L_1$)	$\alpha_3 = 1.024631$
Angle, ($\theta = \text{atan}(L_1/L_2)$	$\theta = 0.77$

Membrane Stress (kg/mm^2)

Short Side Plates: Membrane stress at C, D; $S_1 = P_e(R + L_2)/t = 0.48$
Long Side Plates: Membrane stress at A, B; $S_2 = P_e(R + L_1)/t = 0.47$
Corner Section: Membrane stress at B-C, $S_3 = (P_e/t)[\sqrt{(L_1^2 + L_2^2)} + R] = 0.65$

Bending Stress (kg/mm^2)

Short Side Plates: Bending stress at C, $S_4=(C_0/2I_1)[2M_A + P_e(2RL_2 - 2RL_1 + L_2^2)] =13.49$
Bending stress at D, $S_5=(C_0/2I_1)[2M_A + P_e(L_2^2 + 2RL_2 - 2RL_1 - L_1^2)] = -7.97$
Long side Plates: Bending stress at A, $S_6 = M_A C_0/I_1 = - 9.16$
Bending Stress at B, $S_7 = (C_0/2I_1)(2M_A + P_e L_2^2) = 13.38$
Corner Section: Bending stress at B-C, $S_8 = M_r C_0/I_1 = 15.38$

Total Stress

Short side plates: Total stress at C, $S_9 = S_1 + S_4 = 13.97$
Total stress at D, $S_{10} = S_1 + S_5 = -7.49$
Long side plates: Total stress at A, $S_{11} = S_2 + S_6 = -8.96$
Total stress at D, $S_{12} = S_2 + S_7 = 13.84$
Corner Section: Total stress at Section B-C, $S_{13} = S_3 + S_8 = 16.04$

Maximum Total Allowable Stress, Sm = 1.5, S_a = 17.46

Total stress at all the locations is less than maximum total allowable stress. Hence, the design is safe.

End Closure of the Rectangular Process Chamber (UG-34, C Factor = 0.2)

Inside length of the longer side, mm: $h = 2L_2 + 2R = 460$
Inside length of the shorter side, mm: $H = 2L_1 + 2R = 450$
Factor Z: $Z = 3.4 - 2.4(H/h) = 1.052174$
Factor depending upon method of attachment: C = 0.2

Required Thickness of the End Closure (UG-34, mm)

$$T_{cl} = H\sqrt{\frac{ZCP_e}{S_a}} = 9.57$$

Provided thickness of the End Closure, mm: $T_e = 16$

Check for Stability

The stress levels at all the locations shall be within code allowable stress levels for the rectangular vessels subjected to internal or external pressure. In addition to this, the four side plates and the two end plates shall also be checked for stability as per Appendix 13-14(b) ASME Section VIII Divn.1 and the cross section of the plates shall be checked for column stability as per Appendix 13-14(c).
Similarly mechanical design of the process chamber outer wall is carried out as per the guidelines given in the code. Design of the flanges is carried out as per Appendix 2, ASME Section VIII Division 1. The design of nozzles and nozzle reinforcement is carried out as per the guidelines given in UG-16, UG-27, UG-28 and UG-45 of ASME Section VIII Division 1.

4.4 Conclusion

The various aspects of mechanical design of the process chamber for EB melting and welding applications have been discussed. The strength calculation for the inner wall of the process chamber of a 10 kW EB melting machine is presented. Comprehensive design of the process chamber includes design of the inner and outer walls, nozzles, nozzle reinforcement, flanges, doors, door hinge, support systems, viewing glass arrangement, vacuum sealing for stroboscopic view port and crucible linear motion systems etc. It also includes thermal hydraulic calculation to work out the cooling water requirements. The detail designs will be presented in future editions.