Heat Flow Condition of Electron Beam Welding using ANSYS

Harinadh Vemanaboina[1] K.B.G.Tilak[2] S.Tarun[3] S.Sumanth Reddy[4] T.Mahesh[5]
[1,2]Assistant Professor [3,4,5]Student
[1,2,3,4,5]Department of Electronics & Communication Engineering
[1,2,3,4,5]Nalla Narasimha Reddy Group of Institutions, Hyderabad-500088

Abstract— Electron Beam welding (EBW) is modelled using a basic Kaplan keyhole formation as in laser beam welding. As high penetration depth to width ratios can be obtained in this process, researchers and engineers are working in enhancing this vacuum based technology of joining the components. This welding technique has several applications in fusion reactor fabrication in various components like vacuum vessel and test blanket modules with different type of steels. This study is focussed on simulating and modelling EBW in terms of the heat flux flow with a surface heat on bead area in the form of Gaussian distribution and when the beam forms keyhole plasma, the heat flow conducted to the base metal is modelled as a frustum distribution. Unlike Laser beam welding, in EBW a portion of the heat would leave out to ambience through the lower end of the bead, this amount of heat is to be apportioned. The heat flow mechanism is calculated using Peclet number from which with empirical formulae power distribution is determined. Peclet number variation as a function of radial distance, penetration depth & distance from wall is calculated. The values obtained may not be directly used in analysis but a correlation is obtained which helps formulating a finite element analysis. The process of weld is evaluated using temperature profiles distributions in weld zone (WZ) and heat affected zone (HAZ) using Ansys software. Weld material used is SS304 and temperature dependent thermal and structural properties are considered. The output obtained is the thermal isotherms around the weld to estimate the heat flux distribution on surface and through the keyhole. The scope of applications where the heat flow is distributed as % contribution would provide guidance in structural joints as in nuclear reactor fabrication applications.

Key words: EBW, Peclet Number, Heat Power Distribution, Ansys Simulation

I. INTRODUCTION

Electron beam welding is having several technological applications where the structural integrity is highly demanding in terms of very low distortions, low heat affected zone with good mechanical properties. The electron beam technique employs high power density supply on to the localized portion of the structure with fine control and producing the low residual stress with narrow weld bead formation. The recent applications in the nuclear sector like fusion reactor structural components and fission reactor components have shown keen demand in the electron beam applications due to the stringent working conditions due to the thermo-mechanical specifications and integrity of the complex structures [1, 2]. In spite of the expensive technique, still the application is explored for demonstrative purposes as well as final engineered products. The understanding of the state of the residual stress and temperature profile at several stages will be very helpful to design the product features like the influential characteristics like metallurgical properties and the liquid melt pool behaviour during the solidification with the material properties. It is a challenging task to implement the conditions like the high temperature properties, structural status and the models. This paper is focussed on the analysis of the electron beam weld process conditions pertaining to the SS 304 L plates with approach of Peclet number analysis where the empirical thermal heat conduction to convection ratio is performed. Also as observed in the similar power density application like Laser beam welding the differences are identified and applied to the analysis based on the thermal isotherms with the heat source input models like Gaussian beam source [3], frustum type heat source models[4].

A. *Formation & Simulation of Welding Process*

The heat energy equations are referenced in many including Frewin et.al.[3] For a isotropic, conductive material with equal coefficient of conductivity k_x, k_y, k_z(W/mK) in all three chosen orthogonal co-ordinates. Equation (1) gives the heat energy in the weld area with temperature, T (*K*) obtained both in spatial, x, y, z (m) and temporal, t (sec), terms. Q (W/m^3 or J/m^{3}s) is the net heat from input and the losses in the form of convection & radiation. Density, ρ, kg/m^3, specific heat capacity, c, give the right hand terms of how much heat is retained with respect to time in the material and how much is taken away with the velocity of welding, v (m/s).The boundary conditions given are $T_0(x, y, z, 0)$ throughout the body at time zero or at the starting of the weld, this is an essential boundary condition. In addition the natural boundary conditions have to applied consisting of normal conduction $K_n \frac{\delta T}{\delta n}$ heat flux q, convection h (T-T$_0$), and the radiation term, $\sigma\varepsilon\ (T^4 - T_0^{\ 4})$

$$kx\frac{\delta^2 T}{\delta^2 x} + ky\frac{\delta^2 T}{\delta^2 y} + kz\frac{\delta^2 T}{\delta^2 z} + Q = \rho c\left[\frac{\delta T}{\delta t} - v\frac{\delta T}{\delta x}\right] \quad (1)$$

Together, the boundary conditions are summed up as:

$$K_n - q + h(T - T0) + \sigma\varepsilon\,(T^4 - T0^4) = 0 \quad (2)$$

When symmetric boundary and insulation boundaries are considered as adiabatic, with no heat flowing through the surface, they are obtained by making convection zero, and conduction zero from the surface. Where, K_n is the thermal conductivity normal to the surface in W/mK, h is the convective heat transfer coefficient in W/m^{2}K, ε is emissivity of surface radiating, σ is the Stefan Boltzmann's constant, which 5.67*10^{-8}, W/m^{2}K^4. When it is difficult to use radiation boundary condition, it is combined to convective heat flux by using a modified coefficient, h_r, for hot rolled steel plates with an error of about 5% is,

$$h_r = 2.4 * 10^{-3} \in T^{1.61} \qquad (3)$$

Radiation inclusion will increase solution time by about three times and hence combined with convection.

B. Peclet Number Definition and Information:

Peclet number gives thermal flow in liquid and from liquid to solid all the equations are from Lucki [5]. Peclet number at top surface of weld is Pe(0) at Z=0 vertical distance and is Pe(z) at any depth z. If the bead is conical or of frustum shape as depth, d increases diameter of width of bead D decreases. Peclet number is a function of weld width, weld speed v, and thermal diffusivity α. Where, a is the radius of source of heat power, m is an empirical multiplier used.

$$Pe(z) = Pe(0)(1\text{-}z/d) \text{ and } Pe(0) = v^*a/2\alpha m \qquad (4)$$

Because of heat flow, the amount of power absorbed, Pl, in the inner side of weld is given as [5]

$$Pl = t\,(m1^*Kmol)^*(Tv\text{-}T0)(2.1995+3.1481Pe(0)\text{-}0.16647Pe(0)\,2+0.01152Pe(0)\,3) \qquad (5)$$

Here, t is the thickness of plate to be welded and m1is empirical value to take care of variation in velocity and thermal conductivity. K*mol* is the thermal conductivity of molten metal. Tv is heat source temperature and T0 is initial temperature.

$$Pt = Pc + Pl \qquad (6)$$

Where Pt is the total power consisting of surface induced, P*c* and P*l* is from the molt metal laterally transferred to the solid base plate along thickness by conduction and in the presence of plasma key hole.

In this study different combinations of P*c* and P*l* are tried and the effect of temperature change, and hence distortion and residual stresses that happen. The Power calculated for different P*t* are shown in Fig. 10. The variation of power for different bead temperatures are shown and at different distances from the centre of the weld.

1) Finite Element for Simulation

The heat equations (1) can be represented in tensor form so the elemental transient heat equation is obtained and later summed to get the system equation which is analysed with time.

$$[K(T)]\{T\} + [C(T)]\{T\} = \{Q(T)\} \qquad (7)$$

Where K is a temperature dependent conductivity matrix.*C* is the temperature dependent capacitance matrix based on specific heat it's product with rate of temperature gives heat. The above equation can be solved numerically, with standard FEM models with Crank Nicholson or Euler time integration models. An initial temperature T_i is assumed *K, C* and *Q* are calculated at that temperature and the next temperature *T* at i+1 is obtained. Again *K, C*&*Q* are calculated and temperature at next temperature interval is calculated. The iteration is continued for convergence of temperature or heat flux values. This is a procedure for transient finite element analysis. In the present study the work is done using Ansys.

C. Finite Element Model

The finite element model of dimensions 40mm X 150 mm X 5mm is used. The AISI 304 austenitic stainless steel material is considered for simulations to be carried out. The convection is applied on all the surface of the plate except on the heat applied area. In the present study AISI type 304 stainless steel is used as it is having many advantages such as low thermal conductivity, high resistance of corrosion and high stability at elevated temperatures. Thus SS304 material is widely used in numerous industries, like nuclear industry, chemical plants, aeronautical and specialized pipe industry.

The properties of a typical stainless steel sheet are given in Table1; the temperature dependent thermal properties for AISI 304 stainless steel material are given in Table 2.

D. Thermal Analysis

The thermal analysis has been carried out with constant heat flux, where the thermal load is applied at a time on the weld area. The load is applied for first 10 sec and the temperature attains fusion in 40seconds. The time step is progressively increased up to time=1000 sec to see the plate cool down to ambient temperature. In the present work Finite Element Analysis of single-pass butt-welding has been carried out with constant heat flux. A simple Butt-joint welding whose welding parameters are consistent to those of Friedman's model with heat input Q= 2000 W is considered and has been simulated using ANSYS. The present thermal Ansys is conducted using element type SOLID70.The element is applicable for three dimensional, steady-state or transient thermal analysis. The element can also compensate for mass transport heat flow from a constant velocity field. In this analysis, element SOLID70 is replaced with by a three-dimensional (3-D) structural element SOLID45.

This element type has a three-dimensional thermal conduction capability and eight nodes with single degree freedom (temperature) at each node. The element is defined by eight nodes having three degrees of freedom at each node (translations in the nodal x, y and z directions). The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities ANSYS. The geometry and meshed model with tetrahedral shape with volume mesh of size 0.02 were shown in Fig 1(a) and Fig 1(b).

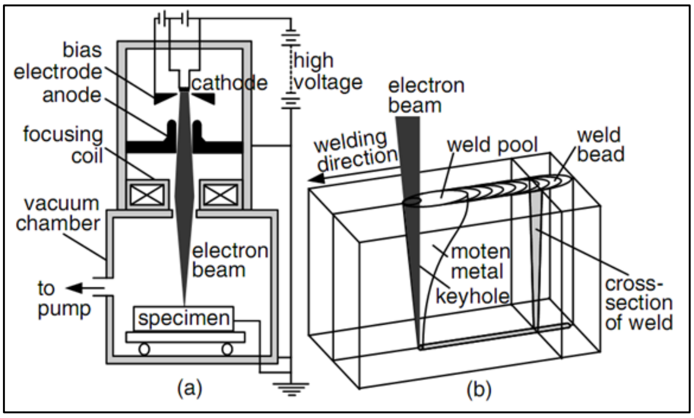

Fig. 1: An Electron Welding Beam generation equipment.

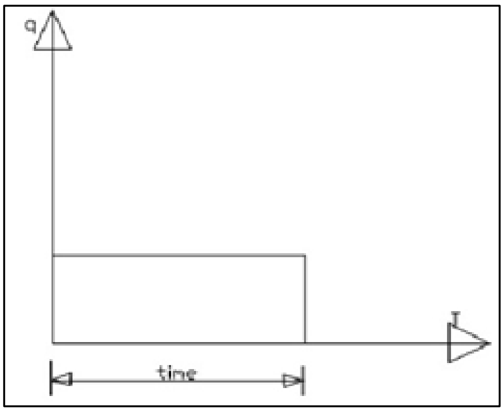

Fig 2a: Mesh model used for analysis

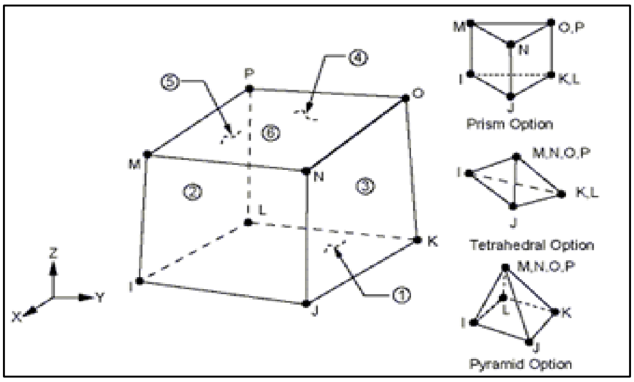

Fig 2(b): Element model used

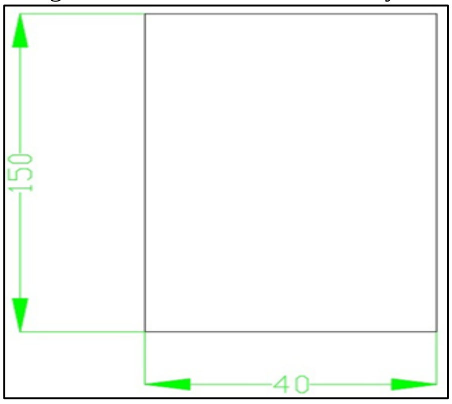

Fig. 3: Geometry of the model (3mm thick)

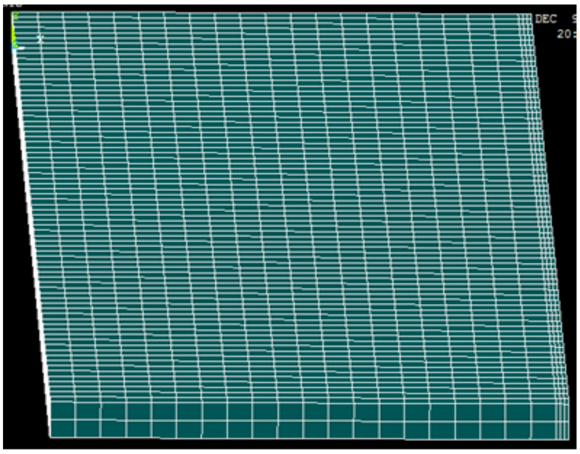

Fig 4: Mesh model used for analysis

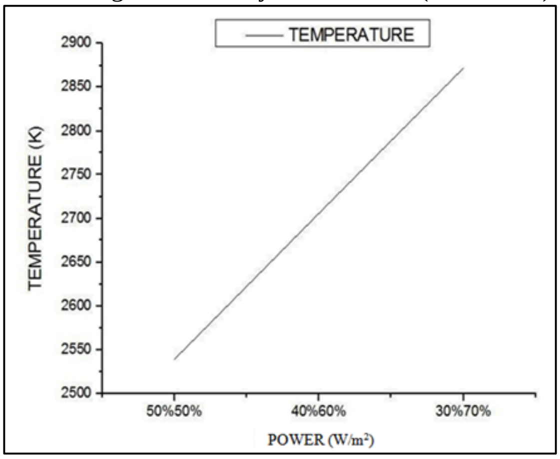

Fig. 5: Power vs temperature distribution

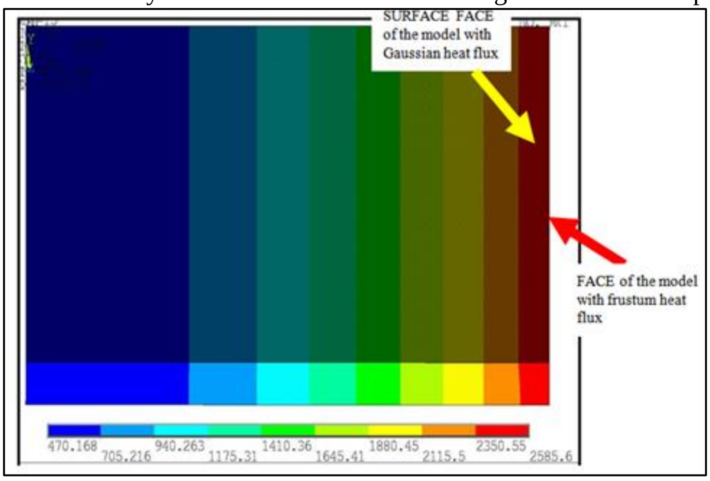

Fig. 6: Temperature distribution of 50% Gaussian -50% Frustum

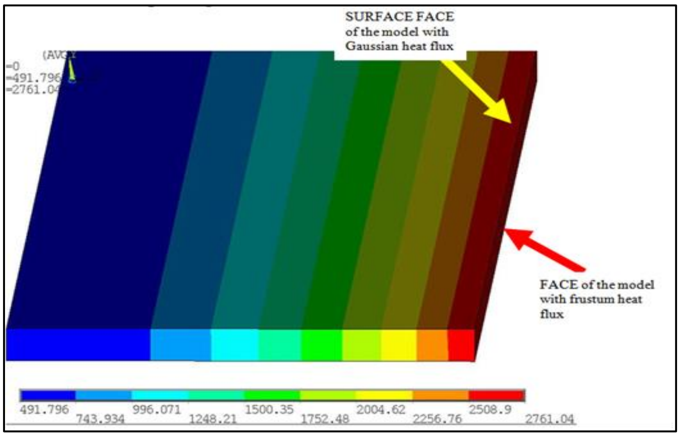

Fig. 7: Temperature distribution (40% Gaussian-60% Frustum of power)

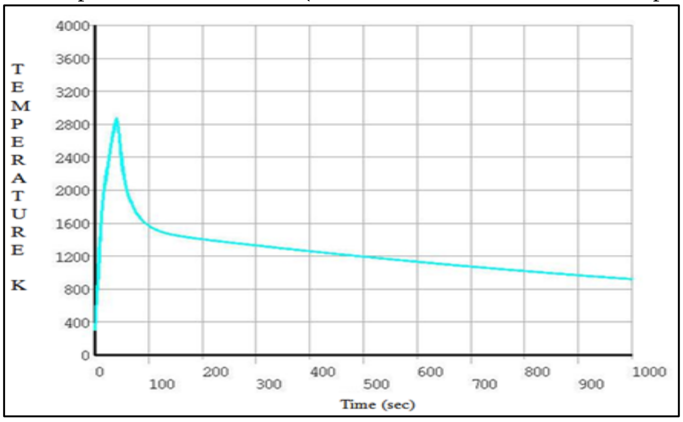

Fig. 7: Temperature distribution of 30% Gaussian -70% Frustum

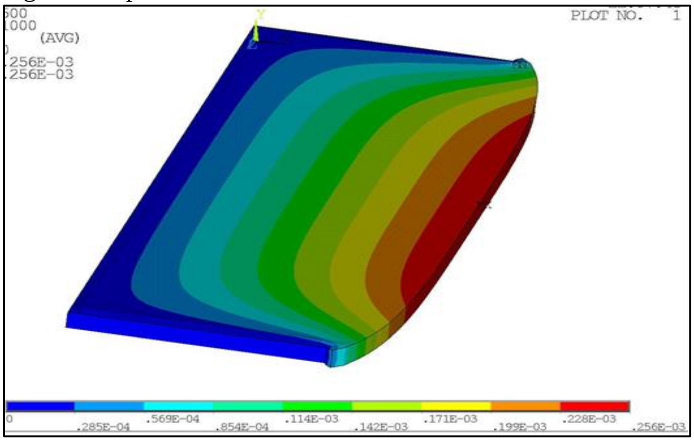

Fig. 8: distortion for 30% Gaussian – 70% Frustum

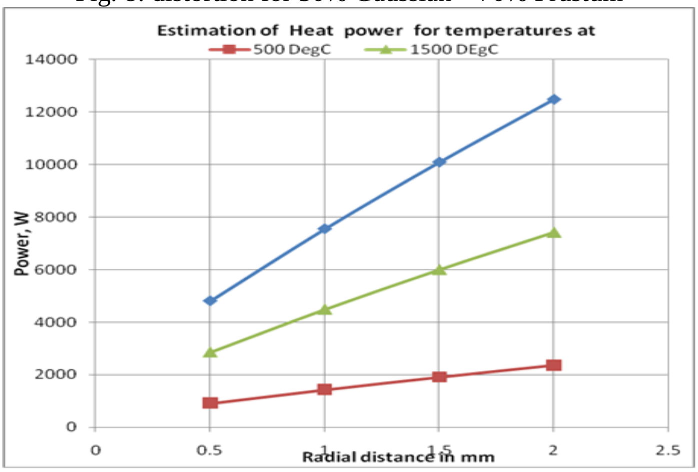

Fig. 10: Power Estimation using Peclet Number

II. RESULTS & DISCUSSIONS

Thermal results with heat flux values obtained from Peclet number and used in heat flux models in EBW

Mechanical properties of AISI 304 Steel are shown in Table 1. As temperature has an effect on both structural and thermal properties its variation is incorporated in the analysis as shown in Table2. The mechanical and thermal properties variation is incorporated in both thermal and structural analysis in the sequentially coupled procedure used.

The temperature distribution was found to be linear, Fig 5. The X axis is a ratio of surface to lateral heat and since the lateral heat is encompassed in the keyhole, convection in molten metal helps in fusion welding and excess heat is transferred to the wall and conducts freely.

The temperature distribution profile with colour coding is shown in Fig.6, for a 50:50 equal distribution of surface and lateral heat the temperature at base is about 470oK and at the bead 2586oK. Similarly, in the 40:60 distribution of heat ratio of surface: Lateral heat it is found that 492oK and 2761oK. In Fig.7, the temperature change in the part at bead variation with time is shown. It is shown for 30:70 ratio of surface to lateral heat and the maximum temperature is 2800oK about 40 seconds after heat is given and after 1000 seconds it is 850oK.

A. Structural Results

The structural results are shown for the power (30% Gaussian -70% Frustum) distribution on the model. Due to the variance in the temperature gradient, the material properties are given in the model for elevated temperatures. A stress acting normal to the direction of weld bead is known as a transverse residual stress. The distortion is shown in the Fig.8 the minimum distortion is at the base metal and the maximum distortion is at the weld bead is 0.2 mm. The minimum Von Mises stress are at the base plate and the maximum Von Mises stress occurs at clamping points 305 MPa otherwise at all other points it is within 110 MPa. shown in the Fig.9. The temperature near the weld bead and heat affected zone rapidly changes with distance from the heat source. This shows more stress value in the weld bead area and gradually decreases from center line to the base plate end. Both distortion & stresses are in acceptable limits in EBW.

III. CONCLUSIONS

An Electron beam welding model using the key hole formation and using the Peclet number is discussed.

- The heat distribution is divided among the two: surface using Gaussian distribution and Frustum distribution for lateral heat.
- A variation in the heat distribution is tried surface heat : lateral heat from equal 50:50 to 30:70 .
- A linearly increasing distribution with temperature getting better at bead with increase in lateral heat entrapped in keyhole is beneficial to obtain weld is observed.
- Weld temperature would be obtained in about 40 seconds and rest of 1000 seconds would be for cooling down to ambient temperature.
- Distortions & stresses are stable with heat flux distribution changes and are well within the acceptable limits 205MPa for strength.

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