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A Welding simulation of dissimilar materials SS304 and Copper

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Abstract

A welding simulation is developed for dissimilar metals followed by a mathematical model for laser beam welding. In this work a Finite element model for dissimilar welding of 304 steel & Copper is done. A simple 3D Sequential thermal followed by structural analysis is done using Ansys software. Temperature dependent thermal and structural properties were used. A static heat load is given representing welding load at the weld joint, Gaussian heat flux distribution is used. The outcome of the heat input is temperature field structural deformation and residual stress formation. First, two like SS plates were joined; next two Copper plates were joined and finally a SS plate was joined to a Copper plate by welding. At the weld joint parameters such as temperature, distortion and residual stresses were obtained and analysed. This study will provide an insight to the designer for obtaining feasibility of providing such a weld and for further fatigue life studies.

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Keywords: Cu – SS welding, Dissimilar material welding, Residual stress, Distortion, Temperature fields.

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1. Introduction

The dissimilar metals joining of stainless steel and copper are having some applications in nuclear industry, chemical and automobile sectors. The joining process poses challenges in the weld process due to the complex melt pool development owing to the difference in the material properties like melting point, thermal conductivity and others. The joining processes like brazing, laser beam welding and electron beam welding are attempted for the manufacture of copper and steel joints with different requirements. Simulation of dissimilar joining process gives the knowledge of the various states of the material during the process with respect to the temperature field, residual stress and deformations. ANSYS based simulations were attempted for welding process for understanding by various authors for similar and dissimilar metals. However, the reports on simulation studies on copper and steels were very less reported due to the complexity involved in the assumption pertaining to the considerations like convection and non linier methodologies to be taken into the models. While in the process of joining, solubility of copper and steels particulates remains undissolved constituents with incomplete phase transformations due to the cooling rates involved with solidification. Simulation offers the insight understanding of the complex temperature state and stress distribution in and around the joint locations with proper selection of input parameters.

Chandraputla & Belegundu (2011), Ramamurthy (2012) have given the basic finite element models for structural and heat transfer processes. From these 1D, 2D & 3D models for finite element simulation can be modeled. Both steady state and transient conditions are given. Linear, quadratic shape functions can be taken as per the accuracy requirement. Goldak (1984) has modeled welding simulation using Finite element method insights to the modeling heat flux as ellipsoid and double ellipsoid models. Another, important shape is a Gaussian distribution which is applicable to Laser, Electron beam or Plasma welding. These models were elaborated and used in Finite element simulation by Akella, Ramesh & Harinadh (2014). A three dimensional welding model for Laser welding was done. Use of Frustum, ellipsoid & Gaussian heat modes was modeled. The present study was focused on the understanding of the dissimilar copper and steel plates joining with simulation using ANSYS. Laser beam joining method was taken into consideration and the developed constant heat flux with Gaussian beam source was used by the authors. A keyhole heat transfer application was done and compared with conduction mode of heat transfer. Turski & Edwards (2009) introduced a contour method for measuring residual stresses at sections in the plate. It would be interesting to apply this method for welded dissimilar materials; the actual stress distribution would be evaluated.

Sachin S., et al, (2003) gave a 2D analysis with FORTRAN programming to analyze Copper to Steel dissimilar joint. The residual stress distribution in transverse direction across the transverse direction is analyzed. The study showed a compressive stress at weld central line for thin sectioned plates below 2 mm, where as it is tensile stress for thicker sections above 3mm. The metal temperature has not reached the melting point in either material. The thermal effects are much more severe than structural parameter differences in dissimilar metals joining. Also, the study of Copper to Stainless steel is more interesting as the conductivity of Copper is about 10 times that of steel; it would be difficult to bring the copper plate to melting point as heat flow is faster than in SS. Joseph A., et al, (2005) evaluated welding of dissimilar pipes of Ferritic & Austenitic material. This study was to understand the possible failure mode of Ferritic side of the joint as applicable to fast breeder test reactor. Failures were at HAZ, residual stress was seen as one of the main reasons for fatigue failures. The study resulted in a solution when Inconel 82 buttering on Ferritic steel side reduced the residual stress at the weld joint. The reduction was on circumferential stress though normal tensile stress remained at 350MPa. Whereas, the circumferential stress without buttering reduced from 280MPa to 160MPa. Also, a stress relieving heat treatment was also carried out before welding.

This practical study induced further interest in the study of dissimilar metals for nuclear reactors. In this study the analysis of Copper to Stainless steel plates is carried out by ANSYS. In Nuclear structures the cooling Copper pipes need to be connected to the SS reactor shells. As copper is a better conductor of heat compared to steel, ten times more than that of steel, it would be an ideal choice as a heat exchanger, provided a strong and secure joint is possible. The present study was carried with three dimensional analyses of the temperature, residual stress & distortion of copper to stainless steel. First model is with Stainless steel plates, next with Copper plates and finally with dissimilar materials of Stainless steel to Copper. Modeling is carried out with Ansys. The study is a first analysis to understand the discontinuity. This is a follow up of earlier study where an experimental study by the authors, Suresh Akella & Ramesh K Buddu, (2012) caused Copper conducting heat and not attaining melting temperature when heat flow was sufficient to melt stainless steel. This analysis model has given similar phenomena.

2. Formation & simulation of welding process

Steady state heat conduction: Many situations of heat flow lead to steady state processes. A human body has a constant temperature under varying external thermal loads by balancing with internal energy generated. A room temperature can be controlled to a stable set temperature by having air conditioning system. A welding process is transient and is in accurate to deal as a steady state process. However, due to the quasi-static formulation a first approximation would be a static model. Heat flow through a metal due to conduction with some possible heat energy, Q, W/m^3. The conduction in x, y & z for an orthotropic heat conduction model is given by Fourier's law of conduction.

$$\mathbf{K_x\, \partial T/\partial x + K_y\, \partial T/\partial y + K_z\, \partial T/\partial z} \qquad (1)$$

Where K_x, K_y, K_z are the thermal conductivity values, W/m °C, in X, Y and Z directions.

Equation (1) gives the 3D heat flow due to conduction through a metal body. As it would occur in a welded plate, with temperature (*K*) obtained in spatial directions x, y, z (m). The conduction of heat causes heat energy to transmit in the material.

$$\mathbf{\partial/\partial x\, (K_x\, \partial T/\partial x) + \partial\, /\partial x\, (K_y\, \partial T/\partial y) + \partial/\partial x\, (K_z\, \partial T/\partial y) + Q = 0} \qquad (2)$$

When the temperature is changing with time due to unsteady state conditions, temporal, t (sec), term is added and transient equations are used:

$$\mathbf{K_x\, (\delta^2 T/\delta^2 x) + K_y\, (\delta^2 T/\delta^2 y) + K_z\, (\delta^2 T/\delta^2 z) + Q = \rho c\, [\delta T/\delta t]} \qquad (3)$$

For an isotropic, conductive material with equal coefficient of conductivity K_x, K_y, K_z (W/m °C) will be equal in all three chosen orthogonal co-ordinates, Q is the net heat input into the material. Density, ρ, kg/m^3, specific heat capacity, c, W/Kg °C, give the right hand terms of how much heat is retained with respect to time in the material.

2.1 Different boundary conditions are possible:

First the temperature on the boundaries is an essential boundary condition. Generally, the heat flow is due to a temperature difference at the surface boundaries which would be a driving force for the heat flow. The boundary conditions given are T(x, y, z, 0) throughout the body at time zero or at the starting of the weld.

Convection boundary condition heat flow h $(T-T_\alpha)$, where h, W/m^2 °C, is the heat transfer coefficient or surface film coefficient of the surrounding fluid, T is metal surface temperature & T_α is the fluid temperature. The conducted heat from the material will flow out by convection to the surrounding fluid. Convection coefficient depends on natural or if flow of inert gas is used it will depend on flow rate. Another way of heat transfer is by radiation, the radiation term, $\boldsymbol{\sigma\varepsilon(T^4-T_\infty^4)}$, 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,

$$\mathbf{h_r = 2.4*10^{-3}\varepsilon T^{1.61}} \qquad (4)$$

Radiation inclusion will increase solution time by about three times and hence combined with convection. The electrical, laser, EB, plasma or other heat energy given to the metal surface is absorbed by the surface as heat flux. The total heat flux, q to the surface is taken as a load boundary condition. The convection terms can be separated as one from the metal surface as a part of heat from the body, $[h_r]T_0$, and one as a load term $[h_r]T_\alpha$

$$[h_r]T_0=h_rT_\infty \quad (5)$$

When symmetric boundary and insulation boundaries are considered as adiabatic, with no heat flowing through the surface, this is equivalent to conduction heat K_x ($\partial T/\partial_x$); assuming x is the surface of symmetry or no conduction heat flow, such as insulated. In some analysis packages, such as Ansys, if no boundary condition is specified on a surface, it is assumed to be insulated.

2.2 Finite element for simulation

As the welding process is a transient heat conduction problem, the functional in Galerkin's formulation, with ϕ, the virtual temperature field:

$$_v\int(1/2)[K_x\, \delta^2T/\delta^2x + K_y\, \delta^2T/\delta^2y + K_z\, \delta^2T/\delta^2z] -2(Q- \rho c\, [\delta T/\partial t])\, dv + {}_{s1}\int qTds + (1/2)\, {}_{s2}\int h\, (T-T\alpha)^2 ds \quad (6)$$

Where in the first integral, the first 3 terms give the thermal stiffness matrix due to conduction, [Kcond].
The Q term gives the body internal heat generated, like latent heat vector, {Qbody}
The last term gives the body heat capacity matrix, [C], in terms of the time derivatives of temperature.
The second integral gives the thermal load due to heat flux on the surface. {q}
The first term in the 3rd integral gives the thermal stiffness matrix due to convection [Kconv]
And the 2nd term in the integral gives the convective load due to the film coefficent, {h}.
Finally the stiffness matrix $[K] = [K_{cond}] + [K_{conv}]$
And the load vector is $\{Q\} = \{Q_{body}\} + \{q\} + \{h\}$.

The heat energy equations in tensor form, the elemental transient heat equation is obtained and later summed to get the system equation which is analysed with time.

$$[K\,(T)]\{T\} + [(T)]\,\{\partial T/\partial t\} = \{Q\,(T)\} \quad (7)$$

Equation (7) 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. Though, the conductivity, specific heat & density are shown as constants, they are taken as temperature dependent. Since, temperature is time dependent in a welding process the evaluation becomes quasi static.

2.3 Finite element model

The finite element model of dimensions 40 mm X 150 mm X 3 mm is used. The AISI 304 austenitic stainless steel and Copper materials were 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 and Copper are 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 body with copper tubes connected are widely used in numerous industries, nuclear reactors, chemical plants, aeronautical and specialized pipe industry. The properties of a typical stainless steel and Copper material are given in Table 1 as per Akella et.al (2014). The temperature dependent thermal properties for AISI 304 stainless steel material are given in Table 2.

Table 1. Mechanical properties of AISI 304 Steel & Copper

Material	Tensile strength	Yield strength	Density	Melting point	Thermal conductivity
SS	515 MPa	205 MPa	8000 kg/m^3	1594^{o}K	40
Cu	210 MPa	129 MPa	8933 Kg/m^3	1356^{o}K	402

Table 2. Temperature dependent thermal properties for AISI 304 Austenitic stainless steels.

S.No.	Temp (K)	Thermal conductivity, W/m ° K	Density, Kg/m^3	Specific heat, J/Kg K
1	200	11	8200	350
2	400	15.5	8000	400
3	600	19	7800	440
4	800	22.5	7600	550
5	1000	26	7500	590
6	1200	30	7400	610
7	1400	34.5	7350	640
8	1600	39.5	7300	680
9	1800	44	7200	720
10	2000	47	7200	760

3.**Thermal Analysis**

The thermal analysis has been carried out with Gaussian heat flux, where the thermal load is applied at a time on the weld area. After the welding processes is completed, the thermal load step is progressively increased up to time=1000 sec to allow the plate to cool down to ambient temperature. In the present work Finite Element Analysis of single-pass butt-welding has been carried out with Gaussian heat flux, with heat input Q = 2000 W is considered and has been simulated using ANSYS.

The present thermal analysis in Ansys is conducted using element type SOLID70. This element type has a three-dimensional thermal conduction capability and eight nodes with single degree freedom (temperature) at each node. Figure 1 gives the model used for analysis, the figure shows for an example where the bead width is 2 mm. Figure 2. shows the meshed model.

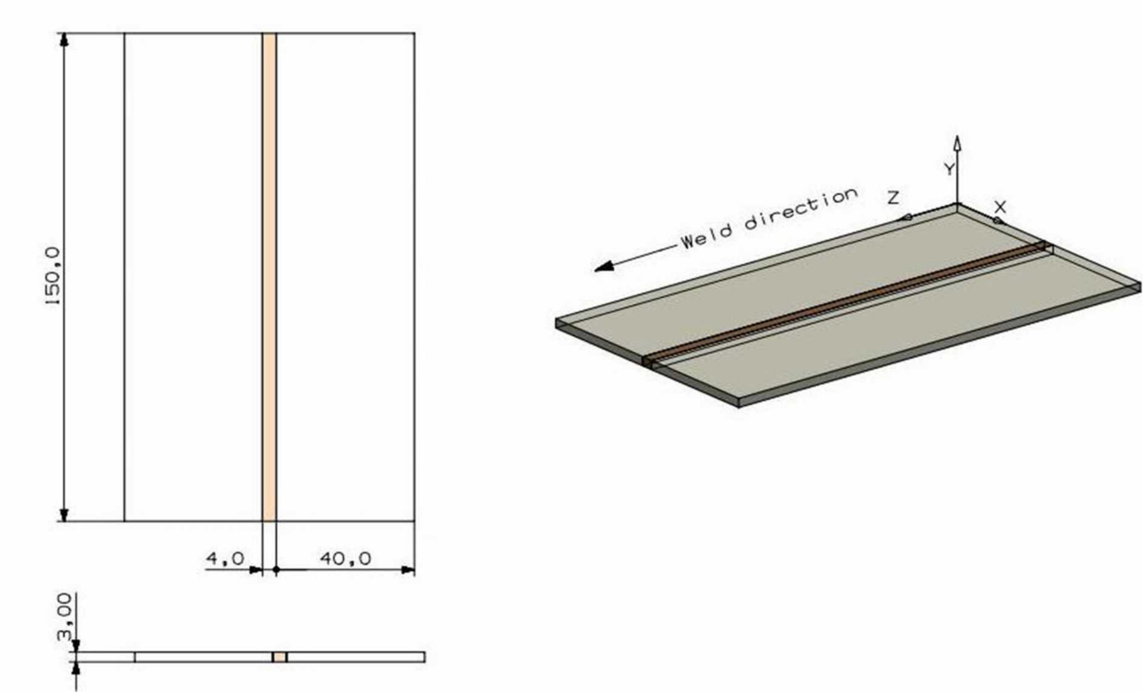

Fig1: Geometry of the model

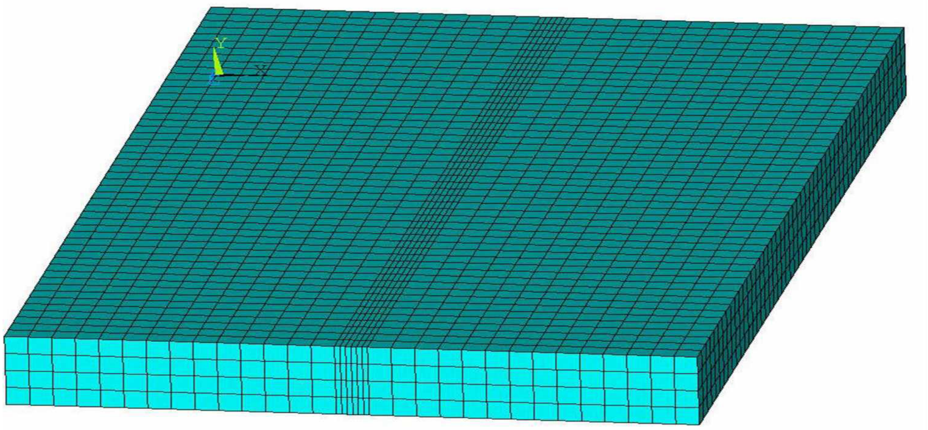

Fig 2: Meshing of the model

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 SOLID 70 is replaced with by a three-dimensional (3-D) structural element SOLID 45. 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.

Assumptions

- Thermal properties, i.e. conductivity, specific heat, density are temperature dependent.
- A combined convection and radiation boundary condition is used on the top surface.
- SS properties were available from literature and for Copper values were interpolated.
- Constant heat flux was used for fusion welding.
- For the structural analysis all the four edges are constrained.

3.1 Thermal analysis

The temperature distribution was evaluated at various zones i.e. fusion zone, FZ, heat affected zone, HAZ and base plate, BP. The 3D temperature distribution is shown in Fig.3. At time t=0, the weld starts with all the constant heat Q, given as input on the surface of weld region. The temperature distributions of the weldments is shown in Figs 3; the fusion zone, is red in color, HAZ is yellow and the rest is in blue color over the base plate.

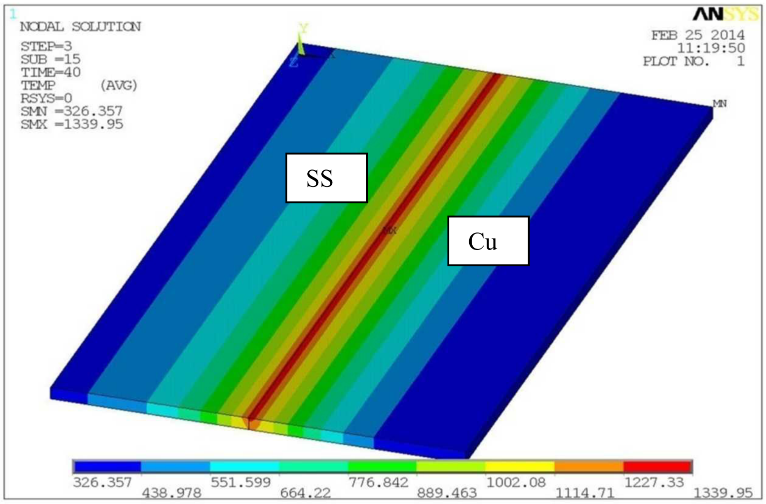

Fig 3: Nodal temperature of the weldment

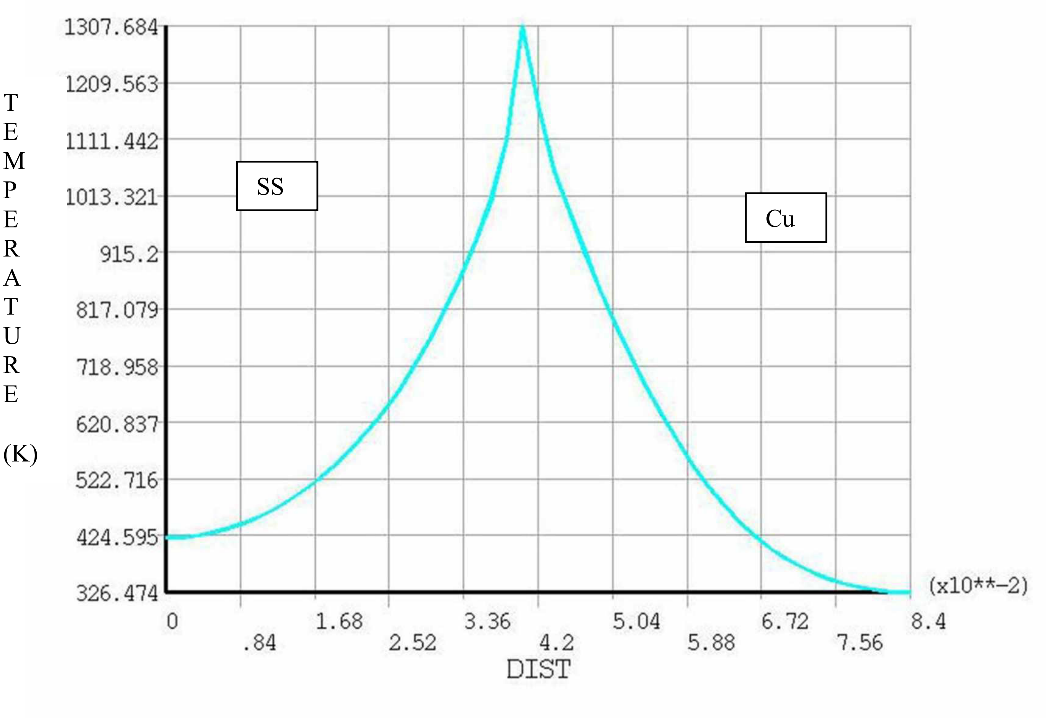

Fig 4: Transverse Distribution of Temperature

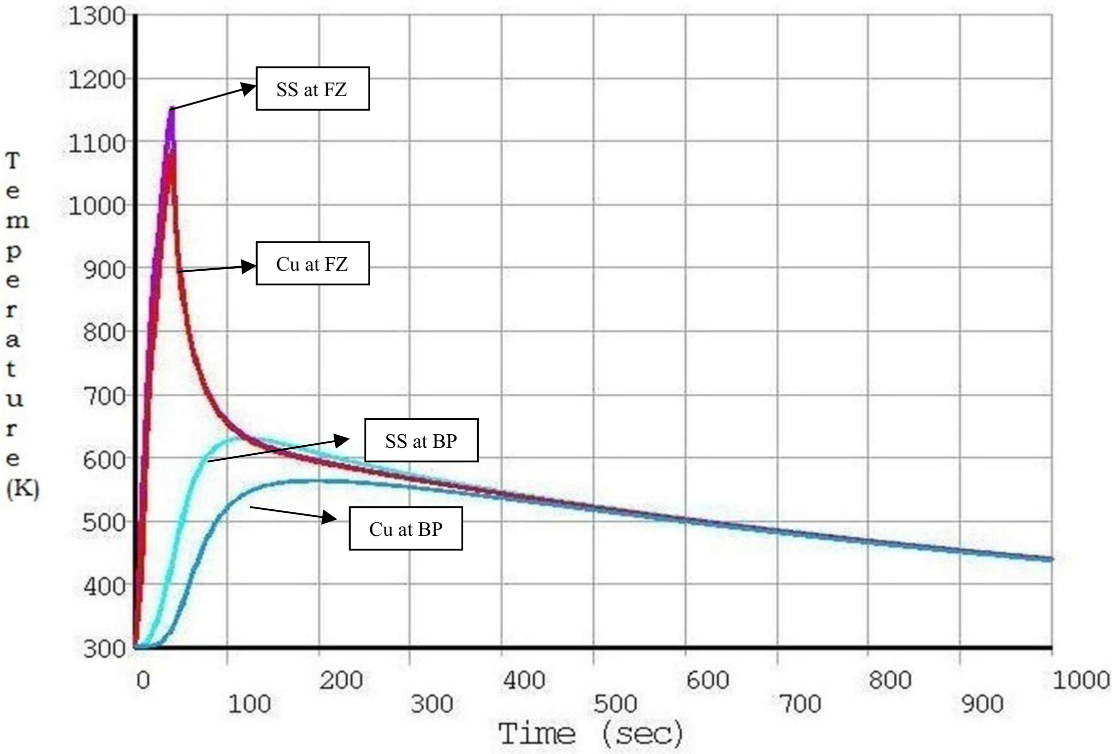

Fig 5: Temperature Distribution of the FZ and Base Plate

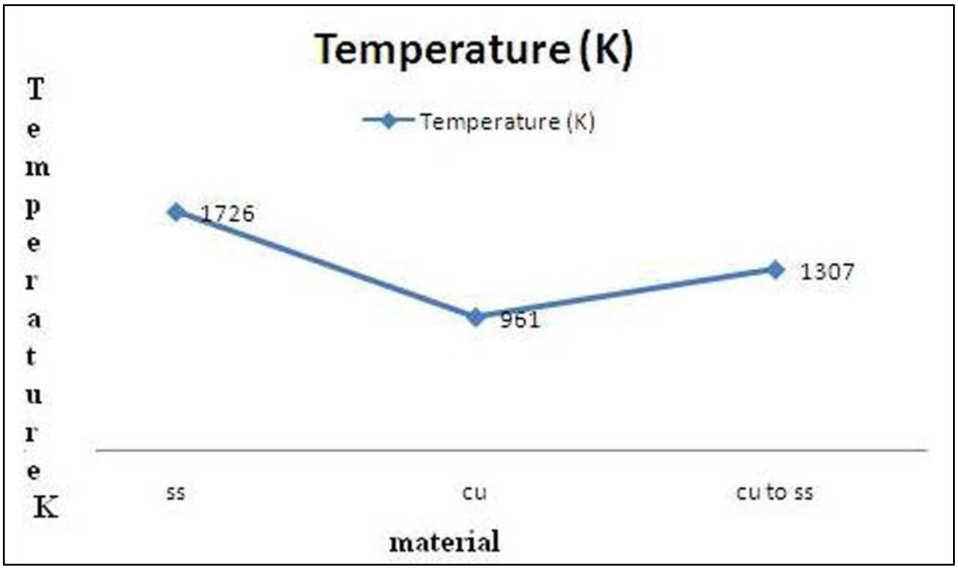

Fig 6: Fusion Zone temperatures of copper, stainless steel & copper to stainless steel

In Fig. 4, the transverse heat distribution is shown. In the weld area the temperature has reached a common peak. The copper plate reaches ambient temperature first. Whereas, the SS part would take more time to come to ambient temperature. In Fig 5 the temperature distribution in the transverse direction on the surface of the weldment is shown. Though the geometry, heat flux & boundary conditions are symmetrically distributed the temperature is found to be asymmetric. The temperature is found to vary from 303^0K in base plate and up to 1307 ^{0} K in the fusion zone with the applied heat input parameters in the developed model.

Fig. 6 gives the comparison between maximum temperatures for same heat of 2 KW under same boundary conditions. SS plates reach 1726^oK, whereas, the copper plates reach only 961^oK, due to the high conductivity, 10 times that of SS, the heat dissipates fast away from fusion zone. Lastly for the dissimilar weld, SS to Cu reaches 1307^oK. It is important to see that SS on one end moderates the heat flow; it acts as a partial insulator and gives a boost to the fusion temperature compared to when the other plate is also copper. As a result the SS plate looses about 419^oC where as in the Cu plate there is an increase of 346^oC.

3.2 Distortion analysis

Fig. 7, gives a 3D distortion field, again a close look reveals the asymmetric nature of distortion. SS distorted compared to the Copper part. Detailed in Fig 8, Copper alone distorts the least $2.2e^{-5}$m. Combined SS and Cu have doubled the distortion and SS alone has a distortion of about 10 times that of Cu + SS.

3.3 Residual stress analysis

The estimate of residual stresses is analyzed in all the regions. Due to the variance in the temperature gradient, the thermal dependent material properties are given in the model. A stress acting normal to the direction of weld bead is known as a transverse residual stress. Fig. 9 gives the transverse stress distribution over the plate which shows a tensile stress, 75 MPa, which is for a short distance across the HAZ. The value changes to compressive stress of about -50 MPa, for the rest of the plate up to the edge. At the edge the free end causes zero stress. The maximum stress value is about 76.90 MPa is much below the yield stress. Figure 10 gives the comparison of maximum stress value for the three cases; SS alone has 79.6 MPa, Cu stress increase to 91.0 MPa. Whereas, at the weld portion, the combined SS and Cu plates have a maximum stress value of 74 MPa.

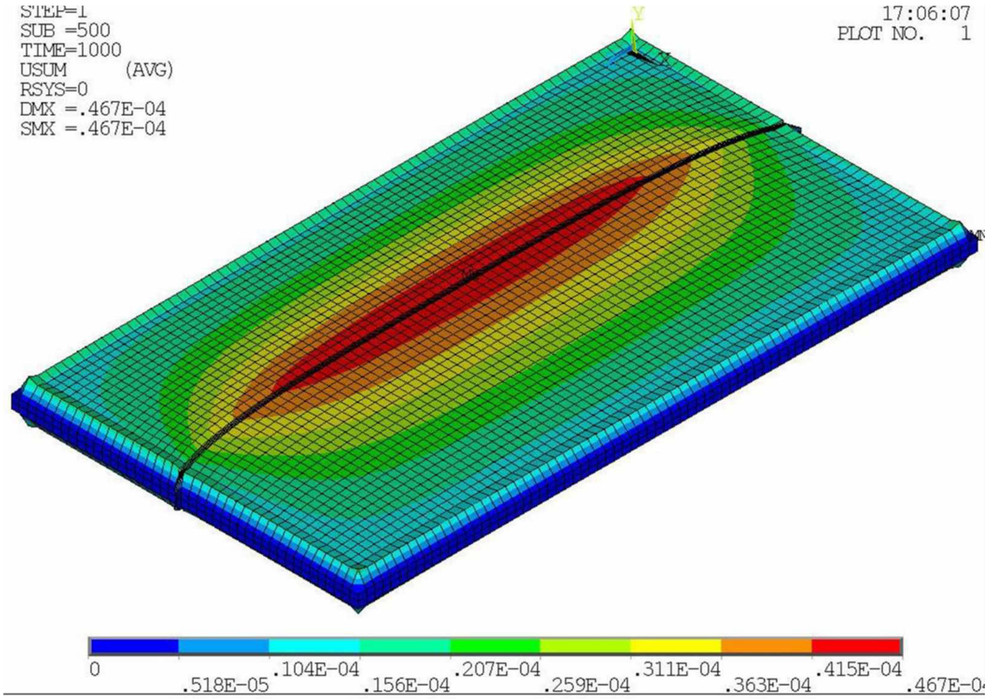

Fig 7: Dissimilar distortion of the weldment

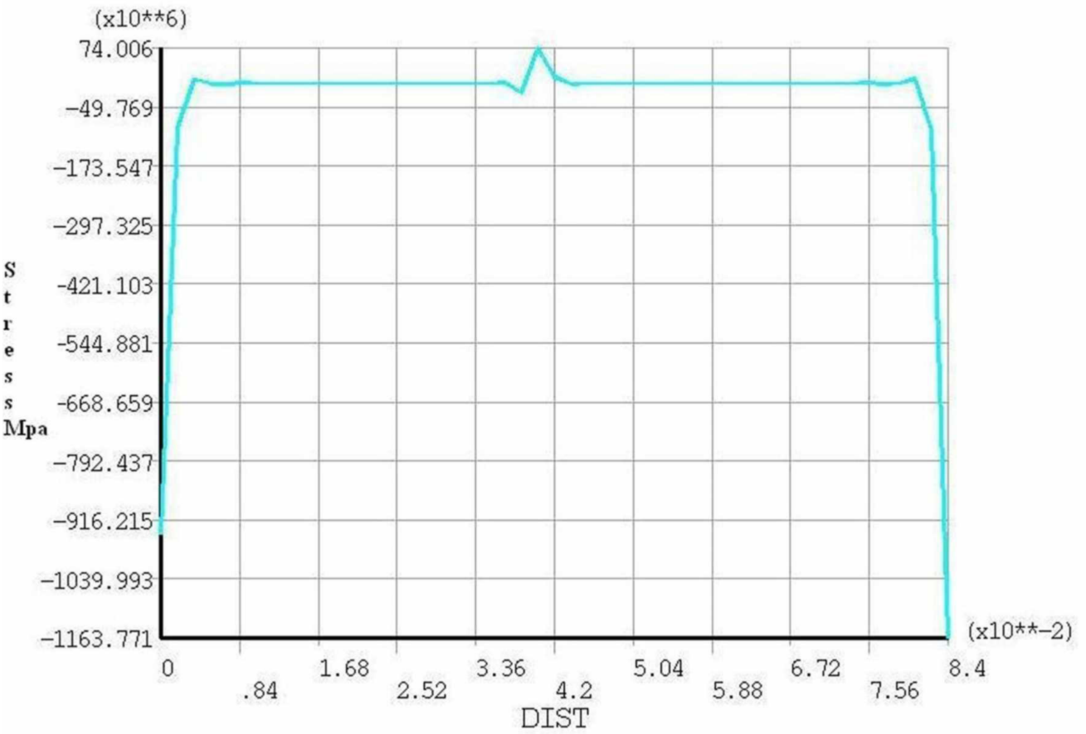

Fig 9: Stresses distribution in transverse direction

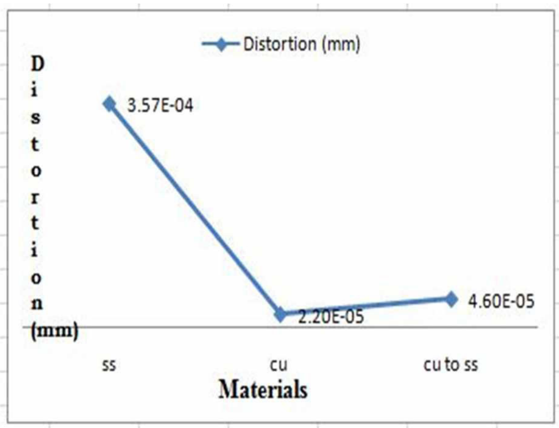

Fig 8: Distortion Comparison

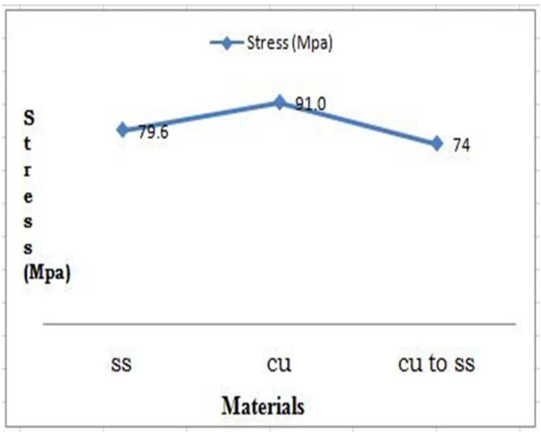

Fig10: Stress Comparison

4. Conclusions

A 3D model of SS304 and Copper plates joining by welding was simulated. A Finite element quasi static, sequential analysis is done using Ansys software. As expected the high thermal conductivity of copper retards the copper plate attaining its melting point. Temperature distribution, distortion & residual stresses are calculated. Individual plots are shown in the transverse direction to show the variation in the copper region to the steel region. Our further work is to do process design of experiments study to make these variations more uniform by controlling critical parameters.

Acknowledgements

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