Estimation the Peak Temperature and Cooling Rates in GMA Welding of AA6061 Plates by Experimentally Validated Numerical Methods

M M Vishwanath, P Harisha and N Lakshamanaswamy

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Vishwanath M M [a*], Harisha P [b], N Lakshamanaswamy [c]

[a] Department of Mechanical Engineering Dr. Ambedkar Institute Technology, Bangalore,VTU, India.
[b] Department of Mechanical Engineering CMR Institute of Technology, Bangalore, VTU, India
[c] Department of Mechanical Engineering UVCE, BUB, Bangalore,
India.Email: [a] vishwanath.malnad@gmail.com, [c] nlsvce@yahoo.co.in
*Corresponding Author

ABSRACT

Numerical simulation is a recent emerging trend in the manufacturing industry. In the present investigation, numerical modeling and simulations are carried out to analyze the peak temperatures and the cooling rates for the temperature field in a gas metal arc welding of AA6061 alloy plates of thickness 6mm, using ANSYS 19.0. Experiments are carried out for the temperature field and heat source models formed at the welded joint. Furthermore, transient thermal simulations are performed for various temperature fields, different heat inputs which are obtained from experimental investigations. Modeling of the sample prepared for experimental investigation is carried out using SOLID EDGE and grid generation by ICEM CFD. This model is subjected to transient thermal simulations to obtain the peak temperature at the welded joint using ANSYS Workbench. The cooling rates are estimated from the simulated results as it is a complex process to estimate experimentally. The model used in the investigation is a Gaussian distributed Double Ellipsoidal heat source model. The numerical simulation and the experimental results for the temperature fields are in good correlation. The results indicate the peak temperature obtained at the weld joint is above the melting point of the base metal, forming a strong joint that increases with the heat input. Higher cooling rates are obtained at high heat inputs due to higher peak temperatures.

Key words: Transient thermal simulations, Double Ellipsoidal heat source model, Temperature Field, Peak temperature, cooling rates.

1. INTRODUCTION

Welding is a conventional manufacturing technique where the intense heat source is appliedon the base metal which melts initially and solidifies fusing the two detached work piece intoa permanent joint. Welding is used for various applications starting from small domestic and automobile components to the large structures. Certain problems such as cracks, deformation, stress, irregular penetration, and gas inclusions may be noticed at the joint during the welding process. The defects are caused by a thermal cycle due to high heat input during welding. Hence it is required to estimate the thermal parameter occurs during welding. The estimation of the Peak Temperature and the cooling rates are very important aspects to studthe weld behaviors to obtain best joint and to avoid defects. In the last few decades investigations on heat transfer behavior are carried experimentally as well as numerically in welding. Arc welding is a most popular, widely used, diversified type of welding where the electric arc is utilized as the heat source. The joint is created by means of the arc developedbetween electrode or a filler metal and the work piece. Gas Metal Arc Welding is a form of Arc Welding in which the arc is maintained in an inert gas atmosphere between a consumable electrode wire and the work piece. .The Gas Metal Arc welding uses Argon gas as inert shielding gas with the continuously fed electrode wire spool that protects the molten weld zone from external reactions. The thermo mechanical analysis during the GMAW is very important to have best welding sequence and optimization.

Several investigations are made with respect to numerical analysis by developing Finite element models by using numerical simulation software like ABACUS, COSMOS, SYSWELD, ANSYS etc. to investigate thermal behavior in different applications of welding. Heat source models are very important for the numerical simulations as the heat distribution equations are dependent factor heat source models initially Rosenthal [1] one dimensional models were developed in the late 1930 and presently is the most popular analytical method for heat distributions in welds. Several investigations made followed by the Rosenthal consist of serious errors in temperature distributions in and near the Fusion and HAZ of welds. Circular disc model in earlier stages was suggested by the Pavelic [2] in 1965 which is two dimensional planar heat source model and applicable in the regions below 15-20% of melting temperature of the weld. The most popular and more realistic heat source model developed by Goldak's [3] The front half of the heat source in this model is one Ellipsoidal source's quadrant, while the back half is another Ellipsoidal source's quadrant, resulting in a Double Ellipsoidal heat source model. The weld bead geometry created in arc welding techniques is similar to the heat source model geometry developed. Tekriwal et. al [4] made a FE Analysis of 3D Transient Heat Transfer in GMA Welding for temperature field, Heat Affected Zone, Molten Pool Zone and peak Temperature by using Finite element software ABACUS. The numerical analysis' anticipated data were found to be quite close to the experimental data. Modeling of the temperature field and weld profile during gas metal arc welding of filled welds was investigated by Kim et. al [5] . Using a 3-D FEA model, they determined temperature profiles, weld pool dimensions, and the nature of the solidified weld pool reinforcing surface. The experimental results and the calculated form and size of the fusion zone of the GMA welds were in good agreement. The cooling rates and weld heat cycles were likewise in good agreement with independent experimental data. Bendaoud et.al [6] conducted a numerical simulation of heat transfer during a hybrid laser–MIG welding of duplex steel UR2507Cu slabs using COMSOL software for numerical simulations. The experiments are conducted to know the temperature field to validate the simulations. The results are well corresponded and makes the simulations valid. Alwan et. al [7] used the control volume approach to do a numerical analysis of the effect of weld – joint preheating on temperature distributions in GMAW, as well as determining cooling rates for 3-D heat transport in the weldment. The preheat temperature influenced the temperature distribution and slowed cooling rates. Wu et. al [8] In laser pulsed gas metal arc welding hybrid welding, numerical study of temperature profile and weld dimension is performed. The computational results demonstrate a good agreement with the experimental data when considering thermal action characteristics from the perspective of macro heat transport. Hybrid welding temperature profiles, cooling rates, and HAZ widths are also computed and compared to pulsed GMAW. Bajpei et al. [9,10] used ANSYS workbench to conduct an experimentally validated computational investigation on the temperature field, residual stresses, and distortion studies in GMAW of AA5052-AA6061 plates. The simulations and results for temperature distributions are very close to the experimental results. In comparison to the AA5052 plate, the AA6061 plate exhibits larger longitudinal and transverse residual stresses as well as less shrinking. ANSYS workbench is used to carry out similar tasks for various welding processes. Vishwanath M M et. al.[10,11,12] made a heat transfer studies on the similar basis on Friction stir welding of AA6061-AA5056 combinations, and in GMAW and GTAW using ANSYS software package . The study focuses on the estimation of temperature field validate the simulation process and the peak temperature and cooling rates are estimated at three different heat inputs in the Gas Metal Arc Welding of AA6061 Aluminum alloy plates. The heat source profiles are modeled using the Solid EDGE software and called in the ICEM CFD to generate grids. The unstructured grid formations are carried for the heat source model in the ICEM CFD of ANSYS 19.0 versions and grids are generated to the work piece as used in the experiment. The material properties, boundary conditions and heat input parameters are applied and solved in ANSYS Workbench.

2. EXPERIMENTAL INVESTIGATIONS

Experimental method is very important to obtain the temperature field and the heat source profiles based on which the simulations are carried to validate the simulation process to obtain the peak temperature and the cooling rates are evaluated mathematically. The experimental work carried helps us to observe and calibrate the weld profiles for proper selection of the heat distribution equations and the corresponding standard heat source models. These heat source models are used for numerical simulations, for estimating the temperature field, peak temperatures and cooling rates at a given heat input. Experimental methods consist of sample preparations and Welding with data acquisition. Sample preparations include edge preparations and preparations for thermocouple fixing to obtain the temperature field. The prepared samples are chemically treated with the 50% nitric acidand 50% water solution to remove impurities before welding.

The experimental methodology involves three steps. First step involves job or workpiece preparations where the raw materials are identified for the welding and the identified raw materials are made to cut into the required dimensions. The cut pieces are made milled to obtain good finishing and checked for the dimensional accuracy using the height gauges andVernier calipers. The machined samples brought to drilling and taping operations forthermocouple mounting and fixing *Figure 1*. The machined samples are chemically treated with the 50% nitric acid and 50% water solution. Second step involves the measurements and data acquisitions, the temperature data’s are obtained by paperless temperature recorder having high performance multiple displays with data acquisition software where the data’s are viewed directly during the experimentations. The temperature distribution data’sare obtained in different graphical forms as indicated by display and at the same time it can be displayed in the Laptop using USB converter and DAQ software combination. The third step involves the experimentation process, where the experiments are carried with Fully Automated Robotized welding machine *Figure 2* in order to get the uniform welding profilesfor GMA welding. The heat source profiles are measured for numerical modeling and simulations, the temperature distribution data’s collected for validating the numerical simulation. The experiments are carried at Centre of Excellence in Welding and Joining, PSG Tech, Coimbatore, Tamilnadu. The GMA welding experiments are made three heat inputs 3.3 kJ/mm, 3.6 kJ/mm, 3.9 kJ/mm to obtain temperature distribution data and weld profile to suitably select the heat source model for numerical simulations. In order to carry out the experimentation the AA6061 samples are used having dimension 150mm x 100 mm having 6mm thickness. The welding is carried on the 150mm side with welding speed of 300mm/min.

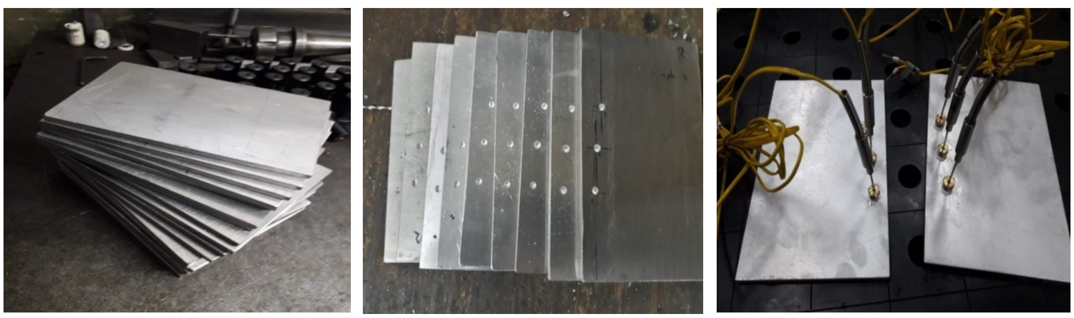

Fig 1. Prepared samples showing Thermocouple locations and fixing to the Samples

Fig.2. Fully Automated GMA Welding Machine with Data Acquisition

3. NUMERICAL INVESTIGATIONS

The numerical investigation consists of Numerical modeling and simulation method followedfor the transient thermal simulations of GMA Welding process, where the temperature field, peak temperature are obtained which also leads to estimation of cooling rate mathematically. The steps involved in the numerical investigation carried in the present study are discussed as follows

3.1 Temperature Dependent Material Properties.

The material used is present work of GMA Welding AA6061 Aluminium alloys and the Temperature dependent properties are presented in the previous work carried by Vishwanath M M et. al. [12, 13]. Temperature dependent properties are important to be considered at the beginning of the numerical simulation as these properties are not uniformwith the time and temperature. The temperature field in the work piece depends on these properties as the heat conduction equation is a dependent factor of material thermal properties. The transient thermal simulation using ANSYS Workbench helps the investigatorto incorporate the thermal properties for the type of the metal used for welding.

3.2 Initial and Boundary conditions:

The numerical simulations carried is a transient thermal analysis for the temperature field and initial conditions need to be specified in the with respect to space and time and is givenby,

$$T(x, y, z, 0) = f(x, y, z) \quad \text{---------- (1)}$$

The boundary conditions used is Homogeneous Neumann Boundary conditions at different boundaries of the work piece and also at the boundaries heat carried away by convection and radiation occurs and hence,

$$Q_{Cr} = Q_{Conv} + Q_{rad} \, Q_{Cr} \quad \text{---------- (2)}$$

$$= h_{total} \, A_s \, (T_s - T_a) \quad \text{---------- (3)}$$

$$h_{total} = h_{con} + \varepsilon\sigma(T_s + T_a)(T^2 + T_a) \quad \text{---------- (4)}$$

Where, A_s and T_s is the surface area and temperature in m^2 and K respectively, Ta is the atmospheric temperature in K, h_{total} is the combined convective and radiative heat transfer coefficient in W/m^2 K

3.3 Modeling and Meshing using ANSYS:

The modeling and meshing of the heat source model and the work pieces are done before the transient thermal simulations. The modeling is done by suitable Solid edge V19 software for the dimensions obtained from the experimental investigations at different heat inputs. Gaussian distributed Goldak's double ellipsoidal Heat source model [3] is chosen based on the experimental observations. the modeled work pieces and heat source models is saved in STEP form and used in ICEM CFD 19.0 ANSYS Software for meshing.

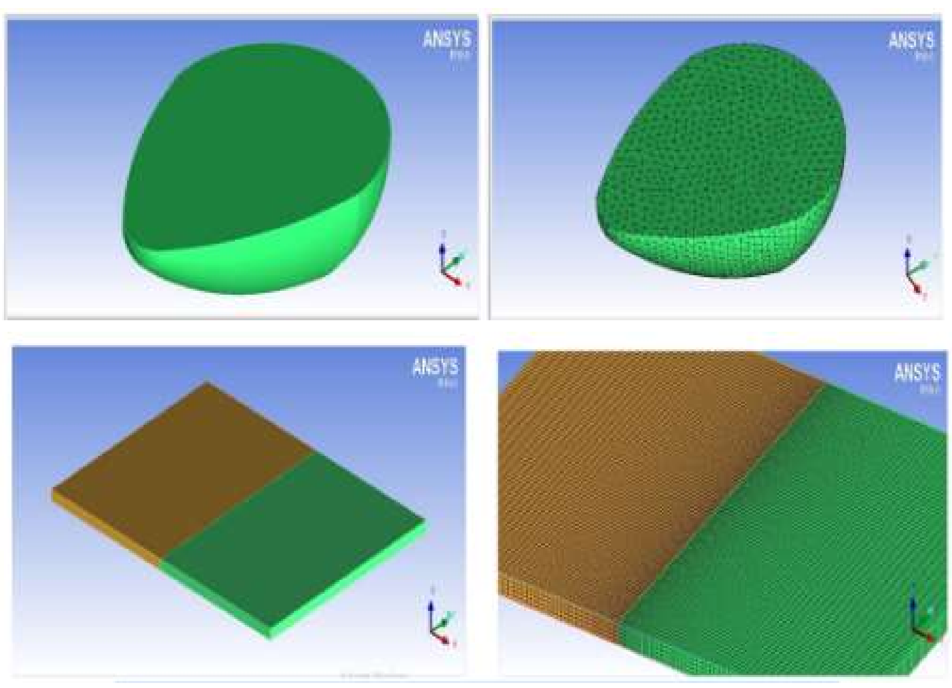

Fig 3. Modeling and meshing of Heat source model and workpiece

The total number of elements obtained is 47121 and the total number of Nodes formed is 8193 and the total number of elements obtained is 24740 and the total number of Nodes formed is 4748 for the work piece which will help in obtaining the nodes at the thermocoupleslocations and the temperature field can be obtained through transient thermal simulations atthat nodes.

3.4 FEA simulation of Temperature contours and peak temperatures

FEA simulation is made in this investigation by ANSYS Workbench 19.0 software. The simulation carried for understanding the temperature field at different thermocouple locations and the peak temperature also observed at different heat inputs as Sample1, Sample2 andSample 3. Temperature data's obtained is compared with the experimental results. The heatinput is given in the numerical simulation as that of experimentation helps in estimating the heat transfer related parameters like peak temperature and cooling rate calculations.

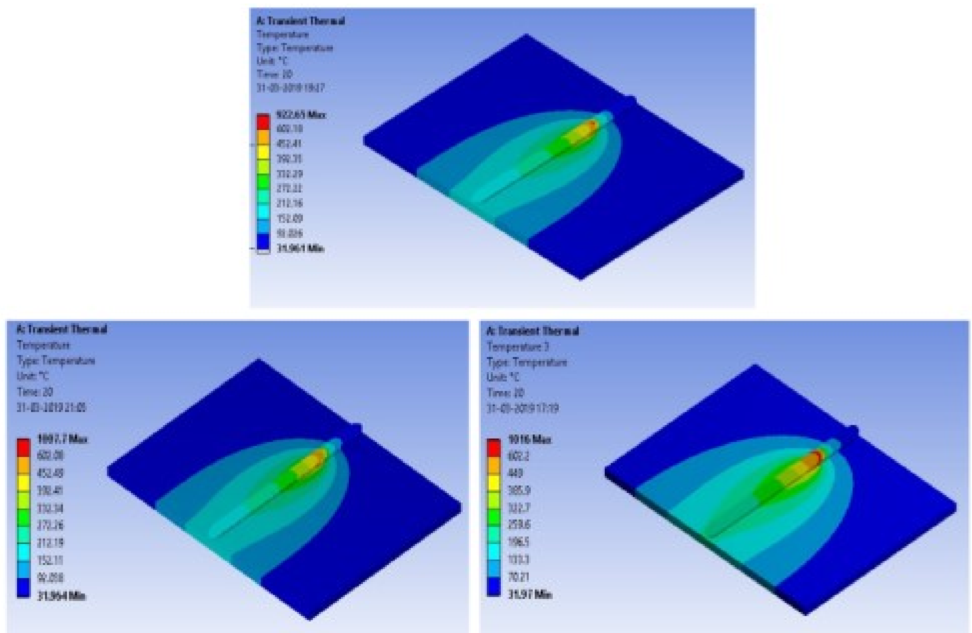

Fig. 4. Temperature contours and peak temperatures of AA6061 plates in GMA welding

Peak temperature generally occurs at the weld centre line during welding which is very difficult to take the temperature data's during welding at the centre line of weld. The numerical simulation process by transient thermal analysis helps to predict the peak temperature using FEA method based on the temperature data obtained during welding of each sample.

3.5 Estimation of Cooling rate in GMA Welding

Cooling in weld plates generally takes place by conduction. The temperature field exhibits arise in temperature followed by the heat loss due to surrounding atmospheric condition, heatabsorbed by the base metal and the clamping devices holding the base metals. The measurement of the temperature to estimate the cooling rate is not complex any non contactor probes can be used to measure temperature at any locations near the weld zone but numerical simulations helps us to estimate the cooling rate at the weld centre. Once the peak temperature obtained from the numerical simulations the cooling rate are calculated. The weldment cooling rate R_C of Gas Metal Arc Welding attained at the weld centre for the can be estimated by Equation

$$R_c = \frac{2\pi K(T_c - T_i)^2}{H_{net}} \quad {}^{\circ}C/s \qquad \text{-------------(5)}$$

Where, K is the Thermal Conductivity of the material used W/m ° C, Tc is the Temperature atwhich the cooling rate is calculated °C, Ti is the initial plate temperature in °C, Hnet is the heat input per unit length J/m.

During Gas Metal Arc Welding, the base metal used is AA6061Aluminium alloy. The cooling rate is determined on each side. The cooling rate estimations for GMAW are summarized in Table 3.1, which is based on peak temperature from simulations. The thermal conductivity of the material AA6061 is 167 W/m˚C, and the initial temperature of the plate is 28˚C, are used for the calculations.

Table 3.1: Estimated cooling rates from numerical simulation for GMAW.

Sl. No.	Welding Speed mm/min	Heat input From Simulation H_{net} (J/mm)	Peak temperature From Simulation Tc(° C)	Initial temperature Tc(° C)	Cooling rate of AA6061 ° C/s
1	70	3400	609.15	28	0.246531
2	70	3600	766.92	28	0.274215
3	70	3900	819.41	28	0.282498

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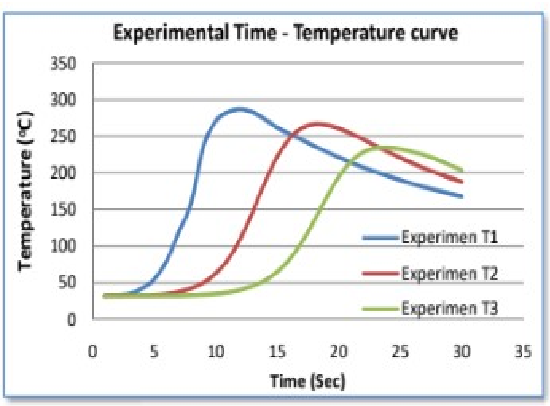
The numerical simulations of welding is not play a very vital role in estimating the cooling rate due to the simulation is restricted to the actual welding process which takes higher computational time. The cooling rate is calculated based on the peak temperature obtainedfrom the numerical simulations and hence the numerical simulation helps in calculating the cooling rate.

4. RESULTS AND DISCUSSIONS

The experimental and numerical simulations based on temperature field and heat source model obtained are carried using Gaussian distributed Double ellipsoidal heat source profile obtained during GMA Welding. The temperature field obtained from the experiments is compared with simulation results and Peak temperature attained at weld centre and the cooling rates are estimated through thetemperature field obtained at different heat input and the heat source profile formed.

Temperature distribution curves in GMA Welding:

Temperature distribution curves are significant to understand the heat distributions and are obtained at different time steps as heat transfer in weld is transient in nature. The temperature distribution curves are plotted for both experimental and numerical simulation results as Temperature – time curves. The Temperature distribution curves at different thermocouple locations are represented in the following Figure.7 and Figure.8 The six thermocouple T1, T2 and T3 are placed at 10mm, 12mm and 16mm on either side of the AA6061 plates from the weld centre and 50mm, 75mm and 100mm from the side where weld begins.



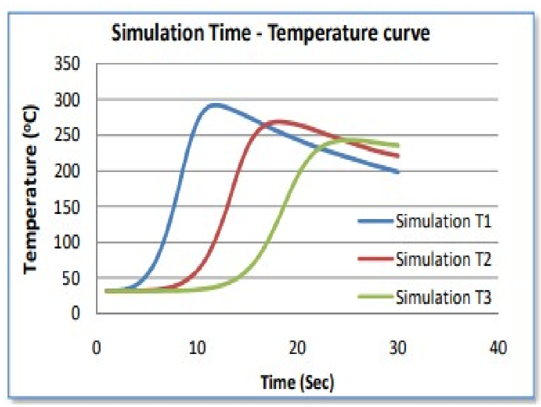


Fig. 5. Comparison of Experimental and simulated Temperature field during GMAW at T1, T2, and T3 from weld centre.

The simulation curves are quite similar to the experimental results, as can be seen in Figures 7 and 8. In a numerical simulation of an AA6061 plate, the peak temperature is 292°C at 12 seconds at 50mm for a thermocouple placed 10mm from the weld centre, 268°C at 18 seconds for a thermocouple placed 75mm and 12mm from the weld centre, and 242.78°C at 24 seconds for a thermocouple placed 100mm and 16mm from the weld centre. Because of the conduction lag caused by thermocouple attachment, there is a 6 second discrepancy in getting the peak temperature. Experimental observations show a curve with a similar shape. It is also observed that after attaining the peak temperature the nature of curve in the experimental line is looks to be more steeper than thenumerically simulated curve indicating the faster cooling rate which is occurred due to the clamping arrangement made during experimentations which absorbs the heat from the sample plates which is not occur during numerical simulations Another important aspect is that the experiments are carried for the three different samples with different heat inputs the heat input details are different in different welding processes due to different joint profiles and their heat requirements. In GMAW the heat source profile obtained is Double Ellipsoidalmodel and three heat inputs 0.33 kJ/mm, 0.36 kJ/mm and 0.39 kJ/mm are considered and the experimented for the temperature distribution curve and the heat source profile dimensions. The heat source profile dimensions are similar in structure with increased dimensions and also the temperature profiles are similar for all the three samples hence for the sample 3 with higher input details are documented for the temperature distribution curve.

Effects of Peak Temperatures in Gas Metal Arc Welding

Peak temperature is the maximum temperature attained at the weld centre during the numerical simulation. The estimation of peak temperature is difficult to during experimentations due to the difficulty in measurement by direct contact and indirect contact are not much accurate due to protective layer around weld.

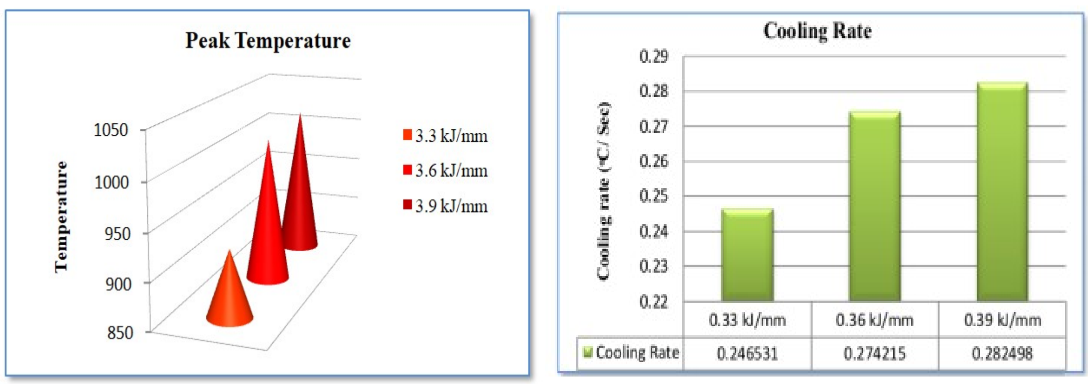


Fig. 6: Peak temperature and cooling rates at different heat inputs in GMA Welding

The three samples at three heat inputs 3.4 kJ/mm, 3.6 kJ/mm and 3.9 kJ/mm respectivelyare consider for the estimation of peak temperature which is obtained at the weld centre line during the time of welding which is very difficult to take the temperature data's during welding at the centre line of weld. The transient thermal simulations helps to predict the peaktemperature using FEA method based on the temperature data obtained during welding of each sample. The peak temperature increases with increase in heat input as shown in Figure 9. The peak temperature also helps us to evaluate the amount of the heat require to form a fusion. The peak temperature are difficult to evaluate through the experimental methods as locating the thermocouple at HAZ is difficult as it damage the thermocouple andits connection and the non contact type of the thermometers also not accurate because of the flux or gas formations around the weld zones.

Effects of Cooling rate in Gas Metal Arc Welding

The results obtained for the cooling of the welded plate is almost similar in all the heat inputsas the cooling rates are considered after the welding. Due higher heat inputs the total cooling time taken is generally more due to high heat absorption near the weld zone. Rate of cooling in all the three heat inputs are same as they are taken after welding. The cooling time may also affected by the surrounding atmosphere and the materials in contact with thesamples holding the samples during welding. *Figure 6* depicts the rate of cooling of specimens at various heat inputs. As the current increases, the cooling rate of the specimen increases. The heat delivered to the specimen increases as the current increases. As a result, deeper weld pools are generated, increasing penetration depth. As a result, it takes longer to chill the specimen, and hence the cooling rate increases.

5. CONCLUSIONS

ANSYS-WORKBENCH is used to carry out the transient thermal analysis for the temperature distributions for process validations with the experimental temperature field at a given thermocouple locations and by observations for Heat Affected Zone and weld zone formed for the considerations of some heat source models. The following conclusions are drawn from the numerical analysis results with experimental validations obtained from GMA welding process.

1. The temperature field obtained from the numerical simulations shows better agreement the experimental temperature field. Hence, the double ellipsoidal heat source model chosen for the numerical simulation process based on the experimental observations can be validated. The temperature distributions curves at the thermocouple locations also helps to consider a node at that point and by FEA analysis it helps us to determine the peak temperature at the weld centre as indicated by the temperature contours. The temperature distribution curves obtained by numerical simulations are in consistent with the experimental results and hence the simulation processes carried are considered to be validated.
2. Three welding is carried with three different heat inputs and the result of transient thermal simulation concludes that the peak temperature increases with the heat input. And also the peak temperature obtained helps us to identify at what extent the joint can melt and form the weld zone. The peak temperature helps in estimating the amount of heat input requires for welding as the actual welding during experiments the measurement of the peak temperature is difficult as it always present at the weld centre.
3. Because of the significant heat absorption around the weld zone, total cooling time takes longer for higher heat inputs. The rate of cooling in all three heat inputs is the same as it is after welding. The heat delivered to the specimen increases as the current increases. As a result, deeper weld pools are generated, increasing penetration depth. As a result, it takes longer to chill the specimen, and so the cooling time decreases.

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