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Empirical and finite element prediction and validation of weld bead profile generated during TIG welding process

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***Abstract*—Welding is a permanent type fastening method used to join to two metal plates together. Tungsten Inert Gas (TIG) welding is a special type of welding technique developed to join metals which are hard to weld. For better weld quality TIG welding is employed to weld ferrous alloys with low weldability used in various engineering applications. The double ellipsoidal heat source is selected to simulate the welding process as it is a suitable heat source for simulating a more realistic welding process. The welding process is simulated mathematically by using empirical relations developed for the double ellipsoidal heat. Further, a code was developed using C Program and the temperature distribution plots were obtained. The weld bead profile is predicted from the plot using the extrapolation method. Further using SYSWELD, Finite Element Analysis software the temperature distribution in the plate is obtained and the bead width and bead depth were found. To validate the empirical and Finite Element prediction and experiment was conducted. In the experimental studies SA 516 Grade 70 steel alloy plate is welded by TIG welding using similar welding parameters as the earlier mathematical studies used for prediction. The weld bead profile from the predicted and experimental results was found to validate each other.**

Keywords- TIG welding; weld quality; Double Ellipsoidal Heat Source; Extrapolation method; Weld Bead Profile and SYSWELD.

I. INTRODUCTION

Welding has been for many years a big part of the manufacturing process in many industries around the world. Welding, among all mechanical joining processes, has been employed at an increasing rate for its advantages in design flexibility, cost savings, reduced overall weight and enhanced structural performance. The advantages of welding do not need further exemplification. Unfortunately the welding process induces also few problems that need to be more accurately identified and after that minimized as much as possible. Among the welding typical problems and most important are the residual stress/strain and the induced distortions in structures. In order to better understand the welding process and its effects on structures, engineers and researchers around the world, covering a large number of industries, have been trying to create algorithms and methodologies to simulate the complete process or just individual phases (e.g. the cooling phase). In recent years, due to the high expansion of computers computations possibilities, many researchers identified the Finite Element Analysis (FEA) as a reliable method for this purpose [1].Gas tungsten arc welding formerly known as tungsten inert gas (TIG) welding is a process that relies upon the formation of an arc between a non-consumable tungsten electrode and the work piece [2].The arc is generally initiated by a high-frequency unit and protected by an inert-gas shroud. The electrode-tip angle determines the spread of the welding arc contained within an envelope of the protective (argon) gas. The gas generates a plasma arc and also protects the molten pool from undesirable oxidation effects from surrounding atmosphere .The GTAW process is one of the most versatile welding processes but it requires a high level of welder skill for manual application. It can be used at current less than 1 A for components up to 0.1 mm thick as well as at higher current for thicker section. GTAW offers great potential in applications where there are arc high demands on weld integrity. Its relatively low deposition rate makes it uneconomic. The Deposition rates can be improved by using hot-wires techniques and narrow-gap preparation.

IV.SELECTION OF HEAT SOURCE MODELS FOR TIG WELDING SIMULATION

The temperature vs. time relationship of welded components and structures can be theoretically obtained by carrying out a heat-transfer analysis of the welding process. This involves many complicated heat-flow phenomena including heat radiation, convection, heat conduction as well as fluid flow of melting weld metal [3]. This process would require solving many constitutive differential equations using finite element or finite difference methods that are time consuming despite the fact that the computing power continues to improve. Therefore, from practical point of view, analytical solutions for the heat-transfer problem in welding are preferable despite their limitations. Their major advantage is that they are given in the closed form equation that could provide the temperature-time information for the welding thermal problems in a rapid and convenient way.Lower-current welding arcs can be treated as a moving-point heat source. Welding heat sources that produce a key hole during the welding, such as electronic beam welding (EBW), laser beam welding (LBW) and plasma arc welding (PAW), should be treated like line heat source. For broad heat sources that envelope an area on a surface (e.g. a large oxygen-acetylene flame) can be considered as a plane heat

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source.Heat source used for welding processes such as electric resistance spot welding, electrical meat explosion welding, arc stud welding and rotational friction welding, where the heat quantity released for welding at fixed location over a relatively short period of time, can be considered as instantaneous heat sources. However, when the heat sources are maintained over a longer period of time such as found in the electric arc or flame welding processes, these are considered to be continuous heat sources [4].Periodic heat sources are those used in pulse arc welding or in resistance seam welding with on-and-off current. In most welding process performed on thick plates, the heat flow is three-dimensional (3D). In order to simulate 3D heat flow, it is necessary to make use of 3D heat source such as spherical or ellipsoidal density heat source [5,6, 7]. In case of welding of relatively thin plates, where a single weld pass is sufficient to penetrate the plate thickness, then two-dimensional (2D) heat flow equation can be used for the analysis using 2 D heat sources. For cases of high power or fast-moving heat sources, the heat flow along the travel direction of the heat source can be neglected, hence, the one-dimensional heat flow can be used to model this situation.For different heat source an analytical approach has been derived by ignoring the complexity of radiation and convection in the thermal analysis of welding process. The temperature-time distribution is obtained by considering the classical heat-conduction equations in solid medium [8].

A. Double Ellipsoidal Heat Source

The double-ellipsoidal heat source is considered to be a more advanced heat source than the single-ellipsoidal source due to its greater flexibility to model realistic shapes of the moving heat source. The double-ellipsoidal heat source is also known in literature [9,10] as Goldak's heat source.John Goldak et al. studied the mathematical models for weld heat sources based on Gaussian distributed of power density in space.

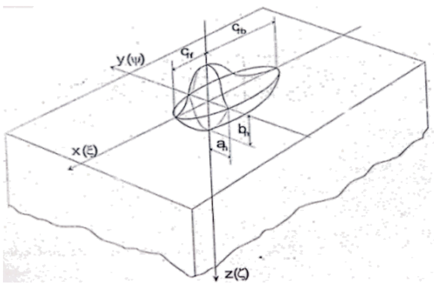


Figure 1 Double-ellipsoidal power density distribution heat sources

The double-ellipsoidal heat source consist of two different semi-ellipsoids, hence, the density within each semi-ellipsoid is described by a different separate equation. The heat density at any arbitrary point (x, y, z) within the double-ellipsoid heat source is shown in Figure 1. The heat density equation for a point (x, y, z) within the front and the rear semi-ellipsoid heat source is described by the two equations below, respectively

$$Q(x,y,z)=\frac{6\sqrt{3}r_f Q}{a_h b_h c_{hf}\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{{c_{hf}}^2}-\frac{3y^2}{{a_h}^2}\frac{3y^2}{{b_h}^2}\right) \quad (1)$$

$$Q(x,y,z)=\frac{6\sqrt{3}r_b Q}{a_h b_h c_{hb}\pi\sqrt{\pi}}\exp\left(-\frac{3x^2}{{c_{hb}}^2}-\frac{3y^2}{{a_h}^2}\frac{3y^2}{{b_h}^2}\right) \quad (2)$$

where a_h, b_h, c_{hf}, c_{hb} – ellipsoidal heat source parameters

Q – arc heat input ($Q=\eta IU$ where I and U are arc voltage, respectively)

r_f, r_b – proportional co-efficient at front and back of heat source, respectively

TABLE 1HEAT SOURCE PARAMETER OF DOUBLE-ELLIPSOIDAL HEAT SOURCE

Sl. No	Welding Parameter	Dimensions (mm)
1.	a_h	7
2.	b_h	2
3.	c_{hf}	8
4.	c_{hb}	16

A program in C was developed and executed to obtain the temperature distribution and from the repeated analysis, temperature history is also obtained at the desired location [11]. Similar logic is used for other moving heat source models. Figure 3.10 shows the temperature distribution along the line y = 0 to 50 at x = 25, at different times. It can be observed that the temperature at point (25, 0) is increasing to infinity as the source approaches to the point. The Heat Source Parameter of double-ellipsoidal heat source given in Table 1 is used for the complete analysis.

I. Finite Element Weld Analysis and Simulation Using SYSWELD

The nonlinear element solver, SYSWELD, is employed to solve the transient analysis of the problem [12]. The peak temperature reached is more than the boiling point of the material and hence the phase change is to be considered while performing the analysis. SA 516 Grade 70 steel alloy plate of length 100 mm, width 90 mm and thickness 10 mm is taken. The heat-affected zone is smaller than the domain of the material. Very fine mesh is created to resolve the temperature distribution in the weld region. The whole domain is discredited into uniform 8-node hexahedrons, consisting of 14927 nodes 18362 and elements. The convection and radiation loads are simulated as surface loads on the element free face with the initial and boundary conditions, the weak formulation of heat conduction equation that describes the transient temperature distribution is obtained in the discrete domain.Also the Temperature Dependent Thermal Properties for SA 516 Grade 70 steel alloy such as thermal conductivity and specific heat is given in Table 2. The cross-sectional and isometric view of the Finite element model is given in Figure 2 and 3.

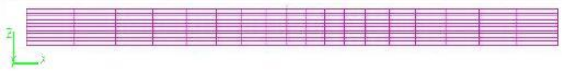


Figure 2 Cross-sectional view of the mesh

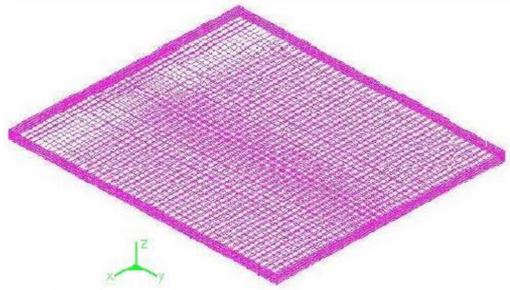


Figure 3 FEA Plate Model

TABLE 2 TEMPERATURE DEPENDENT THERMAL PROPERTIES FOR SA 516 GRADE 70 STEEL ALLOY

Sl. No	Temperature (K)	Thermal Conductivity (W/m K)	Specific heat (J/kg K)
1.	273	51.90	450
2.	373	51.10	499.2
3.	273	51.90	450
4.	373	51.10	499.2
5.	573	46.10	565.5
6.	723	41.05	630.5
7.	823	37.50	705.5
8.	873	35.60	773.3
9.	993	30.64	1080.4
10.	1073	26	931

A. Boundary Condition

- The work piece initial temperature is 30º C (or) 303 K.
- The heat source is moving while the work piece is fixed.
- All the thermo-physical properties for SA 516 Grade 70 steel alloy is considered to be temperature dependent.
- The latent heat of fusion and vaporization are247 kJ/kg and 7600 kJ/kg respectively.

II. Experimental Setup

The welding in the plate is done in such a way that linear segment of the weld bead run on the top of the plate. The experiments where run on the samplewith the welding parameter of the TIG welding process like welding current I, welding voltage U, welding speed v, Gas Flow litre/min as given in Table 3. The schematic view of experimental setup is shown in Figure 4.

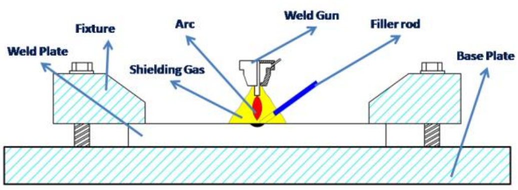


Figure 4 Schematic View of Experimental Setup

Since the welding is done manually the welding speed for each specimen is calculate form the weld length and time taken from the start to finish of the weld.

TABLE 3WELDING PARAMETERDETAILS

Current (I)	26 (Amps)
Voltage (V)	230 (volts)
Arc Efficiency (ή)	0.8
Heat Input (q)	4784 J/s (or) W
Melting Point	1400ºC

III. Results and Discussion

The empirical, finite element method and experimental analysis were done and based on the results the weld bead profile is calculated.

A. Weld bead prediction using Double Ellipsoidal heat Source

The double ellipsoidal heat source was found to be the best suited heat source and the mathematical simulation was done and is presented in Table 4. The temperature distribution from the simulation is obtained along the width and depth of the plate after 5 seconds. The temperature distribution plot along the plate width and depth is plotted as given in Figure 5 and 6.

TABLE 4 TEMPERATURE PROFILE AT 5 SEC.

Sl. NO	Bead Width		Bead Depth	
	Plate Width (mm)	Temperature (K)	Plate Depth (mm)	Temperature (K)
1.	0	2354.1113	0	2354.1113
2.	2	1897.8617	2	1809.0486
3.	4	1164.9642	4	1067.7036
4.	6	737.21039	6	696.52228
5.	8	537.11957	8	520.55444
6.	10	435.86737	10	428.0513
7.	12	380.61707	12	376.60254
8.	14	349.10657	14	346.92459
9.	16	330.62973	16	329.39682
10.	18	319.60815	18	318.89261
11.	20	312.97025	20	312.54742
12.	22	308.95688	22	308.70429
13.	24	306.53201	24	306.38031
14.	26	305.07336	26	304.98221
15.	28	304.20255	28	304.14795
16.	30	303.68796	30	303.65549
17.	32	303.3876	32	303.36847
18.	34	303.21478	34	303.20367
19.	36	303.11694	36	303.11057
20.	38	303.0625	38	303.0589
21.	40	303.03275	40	303.03076
22.	42	303.01682	42	303.01575
23.	44	303.00845	44	303.0079
24.	46	303.00418	46	303.00388
25.	48	303.00201	48	303.00186
26.	50	303.00095	50	303.00089

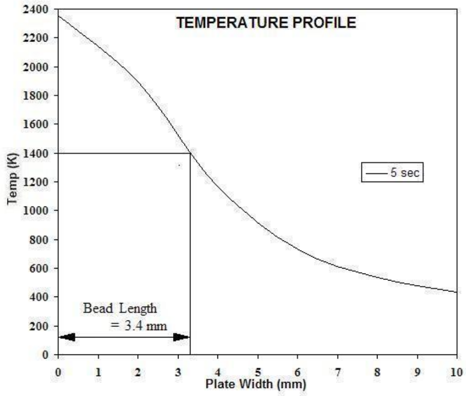


Figure 5 Calculation of Bead Length from Temperature Profile Plot

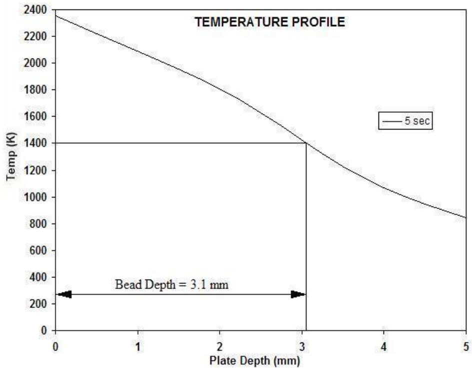
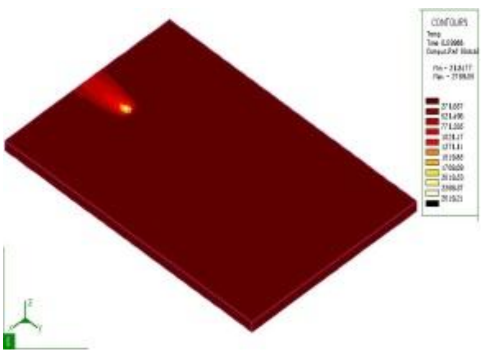


Figure 6 Calculation of Bead Depth from Temperature Profile Plot

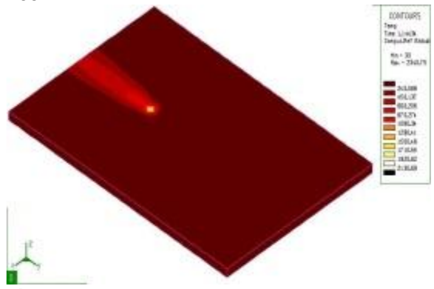
Using the extrapolation method [13] and keeping the melting point temperature of the plate is kept as 1400 K the weld bead with and depth of penetration can be estimated. It is found that both matches nearer to the measured bead profile.

B. *Weld bead prediction using Finite Element Method*

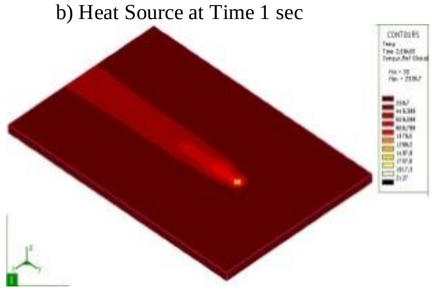
The temperature contour for the simulated TIG welding is found by using the SYSWELD software and the plot of the temperature profile is obtained along the surface and the depth of plate. By the same welding parameters the simulation is done the different temperature profile is obtained. These data can be used for other welding related studies like stress prediction after welding, distortion and weld pool profile. In Figure 7 the four stages of the welding source movement aredepicted and the temperature values are given.



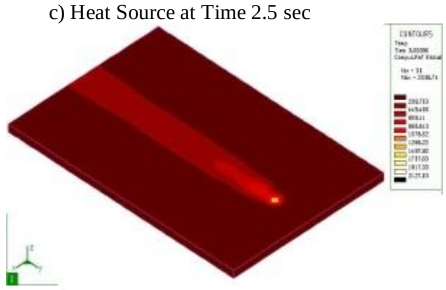
a) Heat Source at Time 0.5 sec



b) Heat Source at Time 1 sec



c) Heat Source at Time 2.5 sec



d) Heat Source at Time 3 sec

Figure 7 Stages of the heat source and temperature distribution in the plate

In this case 23 nodes are selected in the FEA model and the temperature distribution plot along the plate width is obtained. After the welding simulation is over the nodes along the depth of the plate is taken at fixed distance from the edges of the plate. And the temperature distribution on each node is obtained. Using the interpolation method and taking the melting point temperature of metal as 1400º C the bead profile is obtained. The width of the bead profile and the depth of the bead profile are found to be 7.2 mm and 3.2mm as shown in Figure 8 and 9.

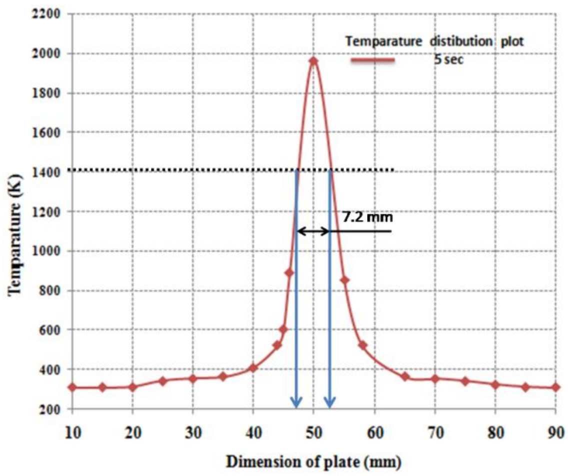


Figure 8 Temperature Profile Plot along the surface of the Plate

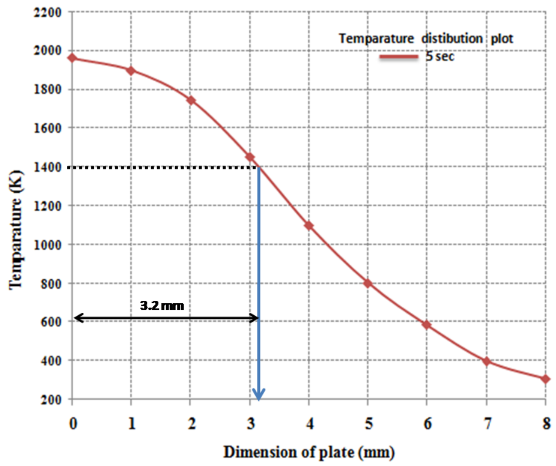


Figure 9 Temperature Profile along the depth of the plate

And the nodes are taken in such a sequence that they lay perpendicular to the weld direction. In this case 23 nodes are selected in the FEA model and the temperature distribution plot along the plate with is obtained. Using the interpolation method and taking the melting point temperature of metal as 1400° C the bead profile is obtained.

C. Weld Bead Profile Measurement on welded plates

The geometry of the weld bead was measured from the bead-on-plate specimen by means of digital photos taken for the top view of the weld-pool shape for welded specimens as shown in Figure 10and transverse cross sectional view of the weld-pool shape for the welded specimens is shown in Figure 11.

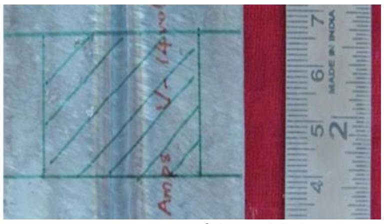


Figure 10 Top views of the welded pieces.

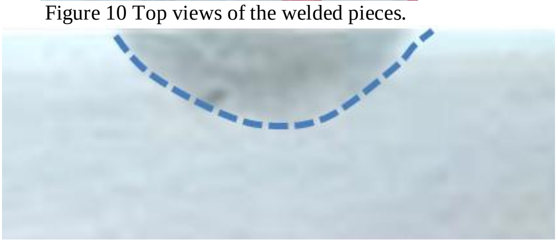


Figure 11 Cross-sectional views of the welded pieces

The experimentally obtained weld pool profile is compared with the Finite Element results and is found to match to a good extent in the Figure 12. The dimensions weld width and weld depth match well with the FEA results.

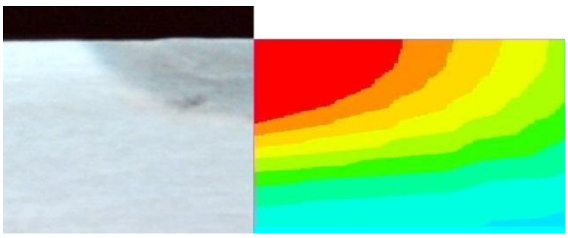


Figure 12 Comparison of Experimental and FEA results

D. Validation of weld bead profile

Initially the double ellipsoidal heat source model was used to develop the temperature profile plot for plate width and plate depth. The weld bead profile such as bead width and depth is predicted using extrapolation method. The finite element method studies were developed with the temperature dependent material properties [14] for better prediction and the welding simulation were carried out. The developed temperature profile from the simulation is used to predict the weld bead width and depth by extrapolation method.

TABLE 5 COMPARISON OF BEAD PROFILES FOR THE THREE METHODS

Sl. No	Methods	Bead width (mm)		Bead depth (mm)	
			Error %		Error %
1.	Experimental	7.3		3.3	
2.	Empirical	6.8	6.84	3.1	6.06
3.	Finite Element Analysis	7.2	1.36	3.2	3.03

The weld bead profile of the experimental investigation is also obtained by using image processing software. The comparison of the three methods were tabulated (Table 5) with experimental method as the reference which was found to have acceptable error percentage.

IV. Conclusion

The prediction of weld bead profile was done by using both the empirical and finite element method. To validate the predicted result an experimental investigation was done. The results obtained had acceptable error percentage.The work can be extended to residual stress distribution in a welded joint. Crack developed after welding can also be analyzed by FEA method. In various sections like T-section, I-section, cylindrical shape etc., can be modelled and simulated. Knowledge of residual stress distribution is further helpful in the assessment of failure of the component.The analysis results help us understand the phenomena governing the welding of a joint, offering insight on the mechanisms and mechanical aspect particular to the welding process. Having understood the welding mechanism, the effects of the welding can be better quantified and therefore can be better addressed in the early stages of the design.

REFERENCES

[1]. Bonifaz E.A., “Finite element Analysis of Heat Flow in Single Pass arc Welds”, Welding journal, pp 121-125, 2000.

[2]. Parmer. R.S., “Welding Process and Technology”, 2nd edition, 2001 (Khanna Publishers, New Delhi).

[3]. N.T.Nguyen, “Thermal Analysis of welds – series : Developments in Heat Transfer” ETRS Pvt Ltd, WIT Press, Australia

[4]. Zacharia, T., Vitek, J.M., &Rapaz, M., “Modeling of fundamental phenomena in welds”, Modeling Simulation Material, Sci.Engg., pp 265-288, 1995.

[5]. Nguyen, N.T., Ohata, A., Matsuoka, K., Sukuki, N. & Maeda, Y., Transient Temperature of Bead-on-Plate Predicted by Double-Ellipsoidal Power Density Moving Heat Source. Paper No. 107, Proc. Of the National Meeting of Japanese Welding Society, No 64, pp. 16-17, 21-23 April, 1999.

[6]. Nguyen, N.T., Analytical Solution for Semi-Infinite Boby Subjected to 3-D Moving Heat Source and Its Application in Weld Pool Simulation. Proc. Of IMPLAST'2000, the 7th International Symposium on Structural Failure and Plasticity, Melbourne, Australia, Eds. X.L. Zhao & G.H. Grzebieta, pp. 819-826, 4-6 October 2000.

[7]. Nguyen, N.T., Mai Y-W., Simpson, S. &Ohta, A., Approximate Analytical Solution for Double-Ellipsoidal Heat Source in Finite Thick Plate, 2002, Welding Journal, 2004.

[8]. Carslaw, H.S. & Jaeger, J.C., "Conduction of Heat in Solid", Oxford University Press, pp. 255, 1967.

[9]. Goldak. J., Chakravarti. A., &Bibby. M., "A Double Ellipsoidal Finite Element Model for Welding Heat Sources, IIW Doc. No. 212-603-85. 1985.

[10]. Pavelic, V., Tanbakuchi, R., Uyehara, R., &Myera, P.S., "Experimental and computed temperature histories in GTAW of thin plates", Welding Journal, V 48, pp 2955-3053, 1969.

[11]. Jeong, S.K. & Cho, H.S., An Analytical Solution to Predict the Transient Temperature Distribution in Fillet Arc Welds. Welding Journals, 76(6), pp. 223s-232s, 1997.

[12]. Mahapatra. M.M., "Three-dimensional finite element analysis to predict the effects of shielded metal arc welding process parameters on temperature distributions and weldment zones in butt and one-sided fillet welds", Journal of Engineering Manufacture, pp 837-845,2005.

[13]. Rayes, M.E.I., Walz, C., &Sepold, G., "The Influence of Various Welding Parameters on Bead Geometry", Supplement to the Welding Journal, pp 147-153, May 2004.

[14]. Chao. Y.J, "Effects of Temperature Dependent Material Properties on Welding Simulation", Journal of Computers and Structures, Vol 80, pp 967-976.2002.