Finite Element Simulation of Temperature Distribution and Residual Stress in Single Bead on Plate Weld Trial using Double Ellipsoidal Heat Source Model

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Abstract*: Tungsten Inert Gas Welding of Ti-6Al-4V plate was simulated using commercial finite element code to predict temperature distribution and residual stress distribution. Because of the geometrical symmetry, only one plate was modelled to reduce the simulation computation time. The temperature dependent material properties of thermal conductivity, Specific heat, density were used for thermal transient analysis. Double ellipsoidal volumetric heat source was used as the heat source model and the heat source parameters were found out by comparing the simulation macrograph and experiment result. Heat source fitting was done using SYSWELD software and the function database was saved after achieving the macrograph similar to experimental macrograph by iteration. The transient thermal analysis was done with Welding Advisor tool which is inbuilt in the VISUAL WELD software using the database obtained from the heat source fitting. The successful completion of TIG welding of Ti-6Al-4V will prove useful in, determining the weld bead geometry, prediction of temperature distribution and residual stress distribution.

***Index Terms*: TIG welding, Heat Source Model, Ti-6Al-4V.**

I. INTRODUCTION

Welding is one of the mostly used fabrication process which is the only method developing monolithic structure accomplished by heat with and or pressure. Because of good characteristics such as strength to weight ratio, excellent weldability and corrosion resistance, Ti-6Al-4V is used in aerospace, Biomedical, ship and chemical industries [1-3]. Tungsten Inert gas is one of the several methods being used for the purpose of joining Ti-6Al-4V. TIG welding is an arc welding process that produces coalescence of metal by heating them with a constricted arc between an electrode and the workpiece (Transferred arc) or the electrode and constricted nozzle (Non transferred arc) [4].

The application of the numerical simulation to the process of welding in the recent decades is growing like anything because of the availability of the high end processor computers and numerous commercial simulation codes. The analysis of welding problem involves thermal, metallurgical and mechanical phenomena simultaneously. The finite element method is often used method to analyse welding problems [5]. SYSWELD has been widely used to simulate simple welding geometry such as butt and T-joint welding and has been shown to provide good results in simulating the single welding process [6].

Heat source modelling is the primary issue in numerical simulation of the temperature distribution. The heat source model is replacement of the physical process with a suitable volumetric heat source or surface volumetric heat source [7]. Double ellipsoidal heat source model is mostly used heat source model because double ellipsoidal shape is very good approximation in many arc welding processes. The Gaussian power density distribution inside a double ellipsoid moving along the welding trajectory was convenient, efficient and accurate for the most realistic welds with simple shapes. When double ellipsoidal model is used in simulation, it is very difficult to select the heat source parameters. The Gaussian heat source parameters were found by trial and error method to validate time temperature history and micrographics dimensions with the experimental result [8].

Residual stresses are caused by the higher temperature gradient generated in and around the weld area due to the generation of heat during welding. The heat generation leads to non-uniform expansion and contraction of the material builds up stresses. The stresses that are not covered by the elasticity in material become residual stress. The effect of residual stresses are distortion and premature failure [9].Numerical simulation technology based on finite element method has already been a powerful and effective tool for obtaining welding residual stresses in the welded structures [10].

In this paper, numerical analysis of TIG welding of Ti-6Al-4V is conducted to predict the weld bead geometry, temperature distribution and residual stress distribution. The validated the macroscopic structure with the experimental result with the numerical simulation result is in good agreement.

II. EXPERIMENTAL WORK

Ti-6Al-4V alloy plate of dimension 200 x 100 x 1.5 mm was used to for experimental work.

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The chemical composition is the material is shown in the Table 1. The plate is roughly polished with the flexible steel wire brush to eliminate the impurities on the surface and cleaned with acetone using tissue paper. The TIG welding was performed using DCEN mode (Direct Current Electrode Negative) using the make of Fronius magic wave 4000.The welding parameters used in this work is given in Table 2.

Table 1: Chemical composition of Ti-6Al-4V

Component	Al	Fe	O	V	Remaining
Weight %	6	0.25	0.2	4	Ti

Table 2: Welding Process Parameters

Current	80 A
Travel Speed	25 mm/min
Arc Length	80 mm
Torch shielding gas flow rate	12 LPM
Trailing shielding gas flow rate	20 LPM

Since the titanium alloy is highly reactive with the environment, a special custom made trailing fixture was developed to protect the molten pool from the environment. The fixture attached with welding torch and moving along with it. The titanium alloy specimen from the bead on plate was cut using Electric Discharge Machine wire cut machine. Since the titanium alloy has the relatively low thermal conductivity compared with the other metals, the cutting was done with water cooling in order to prevent local heating. The velocity of cutting wire and the feed rate were selected carefully to avoid local heating. Mechanical polishing was used to prepare the macro section for the Ti-6Al-4V specimen. The etchant with the combination of 2% of HF, 3% of HNO3 and 95% of water called as Kroll's agent which is the excellent etchant for titanium alloys was used.

III. FINITE ELEMENT ANALYSIS

FINITE ELEMENT MODEL

Numerical analysis was carried out by ESI welding suite software package, which solves the transient thermal equation with the help of finite element method. The finite element model is shown in the Fig.1. It has 28022 nodes and 32704 elements.

Fine meshing was done near to the weld centre line for a length of 7 mm and coarse meshing was done for the remaining. Because of the geometrical symmetry, only one plate was modelled to reduce the simulation computation time. The VISUAL WELD software package was used to create the finite element model.

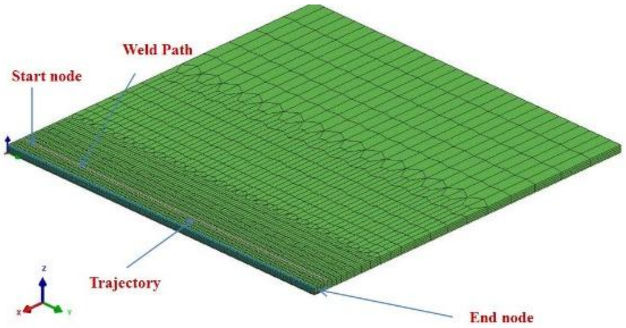

Fig.1.Finite Element mesh model

B.HEAT SOURCE MODEL

The general heat conduction equation in rectangular coordinates is given as

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{\alpha}\frac{\delta T}{\delta t} \qquad (1)$$

Where α is known as thermal diffusivity of the material and defined as measure of the transient thermal response of a material to a change in temperature.

When welding process is considered, there is a volumetric generation of heat which modifies the equation as

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{Q}{k}=\frac{1}{\alpha}\frac{\delta T}{\delta t} \qquad (2)$$

Where k -Thermal conductivity of material, Q -Volumetric heat source (W/m^3)

Temperature is the function of spatial coordinates and time, which can be expressed as T(x, y, z, t).If temperature distribution is to be known at any distance (ξ) from the heat source, It is comfortable to introduce a new coordinate system T(ξ, y, z, t)instead of T(x, y, z, t) Now the governing equation for the welding heat transfer analysis can be given as

$$\frac{\partial^2 T}{\partial \xi^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{Q}{k}=\frac{1}{\alpha}\frac{\delta T}{\delta t} \qquad (3)$$

Since the weld produced by the TIG welding is deep penetration weld, it is essential to select a heat source which is capable of analysing thermal history of deep penetration weld. In this manner, a double ellipsoidal heat source model was selected for this present study. This model is based on Gaussian power density distribution.

The double ellipsoidal model comprises of two ellipsoids namely front ellipsoidal heat source and rear ellipsoidal heat source. The governing equations for the frontal heat source and rear heat source are given as follows.

$$q_f=\frac{6\sqrt{3}f_f}{a_f bc\pi\sqrt{\pi}}\exp\left(\frac{-3\xi^2}{a_f^2}-\frac{-3y^2}{b^2}-\frac{3z^2}{c^2}\right) \qquad (4)$$

$$q_r=\frac{6\sqrt{3}f_r}{a_r bc\pi\sqrt{\pi}}\exp\left(\frac{-3\varepsilon^2}{a_r^2}-\frac{-3y^2}{b^2}-\frac{3z^2}{c^2}\right) \qquad (5)$$

Where f_f and f_r bare represented as weighing functions and from most of the literature it is found that it is satisfying the relation $f_f + f_r = 2$ .The parameters a ,b and c are called as Gaussian distribution parameters and are represented as parallel to the semi-ellipsoidal axes x, y, z respectively.

C.HEAT INPUT FITTING

The SYSWELD is one of the finite element analysis package can be sued to analysis thermo-mechanical, metallurgical calculation of the welding and heat treatment. This package has a facility to fit the 2D Gaussian, Double ellipsoidal, conical heat source and allows in generating custom heat source using FORTRAN code. The heat input fitting tool requires the geometry of the model, material model and process parameters like power and Gaussian parameters to generate the macrograph of the weld. The heat source parameters are adjusted iteratively until obtaining the fusion zone as same as the macrograph of specimen obtained from experiment. Heat source parameters which are found by iteration is shown in Table 3.

Table 3: Heat source Parameters

Parameter	Value
Q_f	9.9 W/mm^3
Q_r	4.95 W/mm^3
a_f	4 mm
a_r	12 mm
b	5.9 mm
c	1.5 mm

The result obtained from the heat source fitting is saved in functional data base to use for the transient thermal analysis.

D.INITIAL AND BOUNDARY CONDITION

It is essential to specify the initial condition since welding process is a transient heat transfer problem, where the temperature field changes with time.

Initial condition is represented as the function of spatial coordinates only.

$$T(0,y,z,t) = T_\infty(x,y,z,t) \qquad (6)$$

Where T_∞ represents the ambient air temperature.

In the welding process, the material is subjected to three modes of heat transfer namely conduction, convection and radiation. From these three modes of heat transfer, the boundary of the material is only subjected to convection and radiation.

The convective heat flux because of the external flow occurring at the surface is represented by the equation as follows.

$$q_{con} = h(T - T_\infty) \qquad (7)$$

Where h - the convective heat transfer coefficient.
The heat flux due to radiation is represents as

$$q_{rad} = \varepsilon\sigma\left(T^4 - T_\infty^4\right) \qquad (8)$$

Where ε -Emissivity of the surface, σ - Stefan–Boltzmann constant and its value is 5.64 x 10-7 W/m2K4.

Table 4: Temperature dependent material properties

Temperature(K)	K (W/mK)	C_p(J/kg K)	ρ (Kg/m^3)
298	7	546	4420
373	7.45	562	4406
473	8.75	584	4395
573	10.15	606	4381
673	11.35	629	4366
773	12.6	651	4350
873	14.2	673	4336
973	15.5	694	4324
1073	17.8	714	4309
1173	20.2	734	4294
1273	22.7	643	4282
1473	22.9	678	4252
1573	23.7	696	4240
1673	24.6	714	4225
1773	25.8	732	4205
1873	27	750	4198
1923	28.4	759	4050
1973	33.4	830	3886
2100	34.6	830	3818
2200	34.6	830	3750
3500	34.6	830	3750

E.MATERIAL PROPERTIES

Due to considerable number of applications, Ti-6Al-4V is considered for analysis and experimentation. The temperature dependent material properties as shown in the table were used to analyse the thermal transient heat transfer welding problem. The liquidus and solidus temperatures are taken as 1950 K and 1877 K.

IV.THERMAL TRANSIENT ANALYSIS

Since welding problem is a thermal transient heat transfer problem, thermal transient analysis is run for 600 sec using VISUAL WELD module which is the product of ESI welding suite.

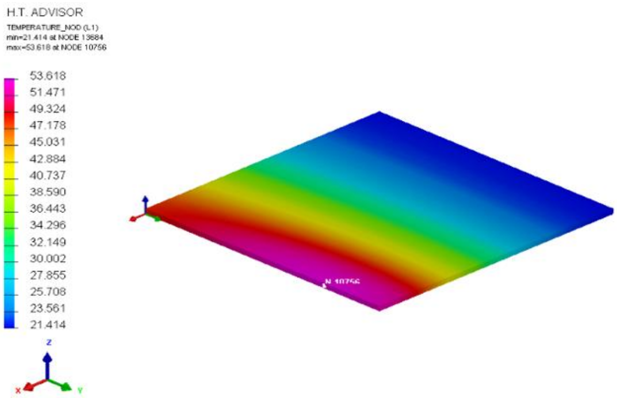

Fig. 2 .Temperature distribution at time = 10

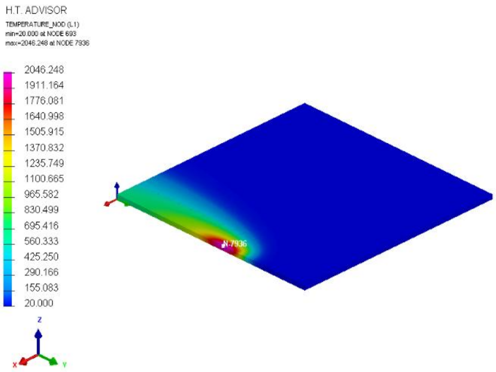

Fig. 3 .Temperature distribution at time = 15 Seconds

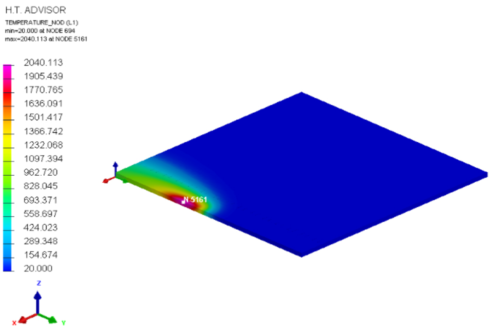

Fig. 4 .Temperature distribution at time = 20 Seconds

ESI welding consists of SYSWELD and Visual Environment package. The welding advisor tool is used to run the thermal transient heat transfer analysis. The heat source model parameters in turn saved as functional data base is defined as heat source for welding run as user defined heat source.

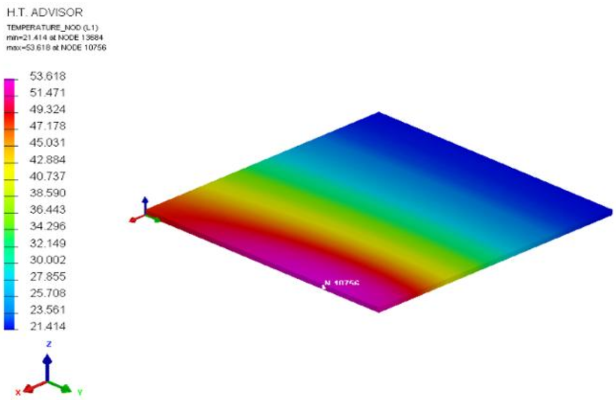

Fig. 5 .Temperature distribution at time = 300 Seconds

IV. RESULT AND DISCUSSIONS

Finite Element simulation for single bead on plate of TIG welded Ti-6Al-4V was run for a time 600s for the welding parameter shown in the table to know the weld bead geometry such as depth of penetration and bead width.

The Fig. 2 - Fig. 5 show the temperature distribution for Ti-6Al-4V 0f 2 mm thickness plate at four different temperatures (10 seconds, 15 seconds, 20 seconds, and 300 seconds) in which the heat input is given as 195 J/mm. From the temperature distribution contour, it is observed that the maximum temperature is 2046˚C.This temperature is maintained during the time between 10 sec to 20 seconds. When the contour is observed for the time 300 seconds, the plate temperature is getting reduced to 53˚c and tries to reach the ambient temperature.

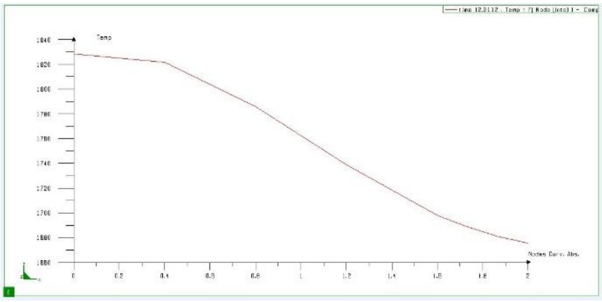

Fig. 6 .Temperature distribution along the thickness of the plate

The Fig. 6 shows the distribution of temperature along the workpiece thickness. It is known that temperature is maximum top of the workpiece and it is getting reduced when distance increases along thickness direction. The melting temperature of Ti-6Al-4V is assumed as 1650˚C and from the figure it is known that full depth of penetration is obtained because the melting temperature is maintained

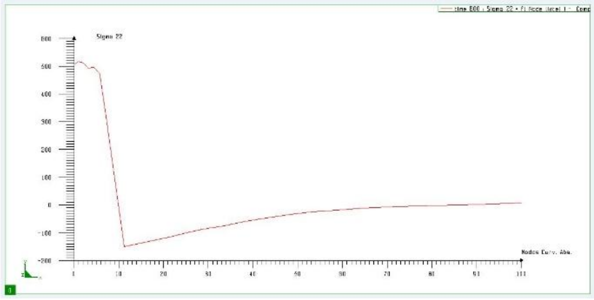

Fig. 7 .Temperature distribution along the transverse direction of the plate from weld centre line

It is possible to know the width of the weld from the figure 7. When a vertical line is drawn from the melting temperature, the width of the weld can be measured. The width of the weld is known as 3.1 mm

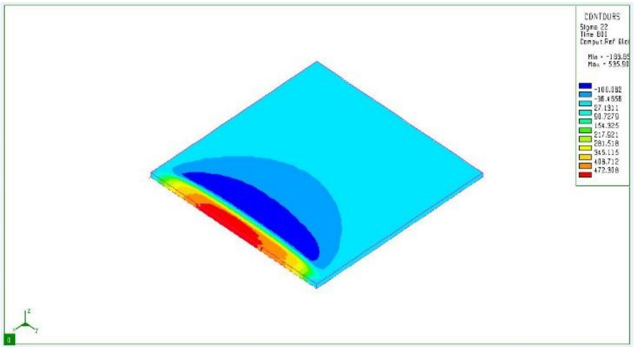

Fig.8 .Distribution of residual stress along axial direction

The Fig. 9 shows the distribution of residual stress along axial direction. The regions near the weld line undergo sever thermal cycles because of the intense concentration of heat in the welding. The thermal cycles cause non-uniform heating and cooling in the material, thus generating inhomogeneous plastic deformation and residual stresses in the weldment. Due to the heating along the weld centerline, the magnitude of residual stress is maximum and tensile in nature. And the residual stress in tensile nature is maintained up to the distance of 0.9 mm from the weld centre line and becomes compressive thereafter. The magnitude of stresses and nature is seen from the figure.

The Fig. 11 shows the distribution of residual stress along the thickness direction. The residual stress is observed as 508 MPa at the top surface at the weld centre line. The magnitude of residual stress increases along the increase in depth and gets maximum value at a distance of 0.8mm from the top surface. When the distance from the top surface increase beyond 0.8 mm along the depth direction, the residual stress decreases and reaches the magnitude of 500Mpa.

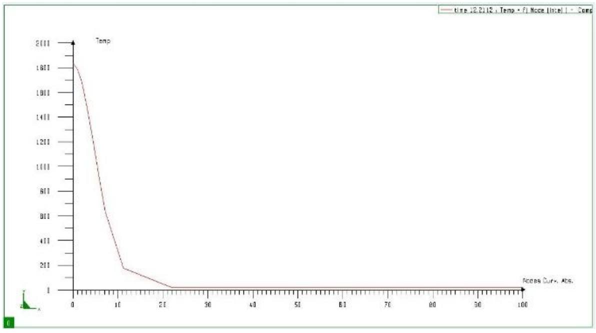

Fig. 9 .Distribution of residual stress along axial direction

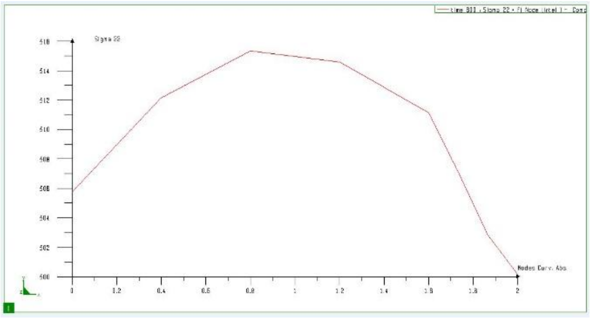

Fig. 10 .Distribution of residual stress along thickness direction

V.CONCLUSIONS

A single bead on plate welding and the finite element simulation of Ti-6Al-4V TIG welded plate was successfully completed using SYSWELD software. The macrograph and weld bead geometry (Bead width, Depth of penetration) obtained from simulation predicted. The residual stress distribution is predicted along the axial direction and it was found that near the weld centreline the residual stress is tensile in nature

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