Proceedings of the
International Conference on Mechanical Engineering 2003
(ICME2003) 26- 28 December 2003, Dhaka, Bangladesh

ICME03-TH-13

ANALYSIS OF TEMP DISTRIBUTION, DISTORTION AND RESIDUAL STRESS FIELD DEVELOPED DURING THE BUTT WELDING PROCESS BY FEA

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ABSTRACT
Heat flow in welding is mainly due to heat input by welding source in a limited zone and it subsequent flow into body of work piece by conduction. A limited amount of heat loss is by a way of convection and radiation. Local Heating and cooling of metal shrinkage on solidification and structural change on solidification cause temperature distribution In the present work, finite element simulation of the welding process induced nonuniform temperature transient, residual stress and bending distortion in a butt welded plate is presented. Residual stresses are greatest in the weld metal and heat affected zone, while the accumulated plastic strain is maximum at the interface of these two on the underside of weldment. Welding experiments are carried out using welding condition identical to those used in the FEA model. The computational results are then verified with the experimental observations.

Key words: Residual stress, Distortion, Welding, Finite Element Method (FEM)

1. INTRODUCTION
In fusion welding, a weldment is locally heated by the welding heat source. Due to non uniform temperature distribution during the thermal cycle, incompatible strains lead to thermal stresses. These incompatible strains due to dimensional changes associated with the solidification of the weld metal (WM), metallurgical transformations, and plastic deformations, are the sources of residual stresses and distortion.

Residual stress distribution and distortion in a welded plate are strongly affected by many parameters and by their interaction. In particular, there are structural, material and welding factors. The structural parameters include geometry of the plate, thickness and width and joint type. Among the material parameters mechanical and physical properties and type of filler metal were considered. Welding process parameters include type of process employed, welding procedure: current, voltage, arc travel speed and arc efficiency. To understand the formation of residual stress, node temperature history during the welding process must be calculated. Physical and mechanical material properties are a function of temperature. In particular, during the weld thermal cycle, material mechanical properties change drastically, especially when material approaches melting temperature. Therefore, due to the temperature dependence of material properties and the large deformation in welding, material and geometrical non-linearity have to be taken into account. The initial expansion of the material due to the temperature increase is constrained by the material placed away from the heat source, therefore generating compressive stress. At a temperature higher than material critical temperature, the material starts exhibiting thermal softening where heating results in decrease of flow stress. As phase change occurs deviatoric stress becomes zero and considerable plastic deformation occurs in the weld metal and the base metal regions near the weld. As temperature decreases during the cooling phase, the stress in the solidifying material increases, and becomes tensile due to the positive temperature gradient. The region placed away from the weld line, will therefore, be in compression since the resultant force and the resultant moment induced by the residual stress evaluated in any plane section must satisfy translation and rotational equilibrium.

2. LITERATURE
A lot of researches have been made to investigate the residual stress and distortion in the welding process. M.Meo and R. Vignjevic [1] have done their work on welding simulation using finite element analysis. They have presented the results of a study aimed at establishing temperature distribution, distortion and residual stress field developed during welding process in welded aluminum plates. The material considered was of AI-2024-T3, commonly used for aircraft components. A numerical analysis of welding process using FEM was carried out. M.V.Deo, P.Michaleris [2] have done their work on experimental verification of distortion analysis of welded stiffeners. The predictive technique employing decoupled 2-D and 3-D approach used for the prediction of the occurrence of buckling

distortion and the magnitude of bowing distortion. 2-D thermo mechanical welding process simulations were performed to determine the residual stress. The critical buckling stress along with the buckling mode was computed in 3-D eigen value analysis. C.Dalle Donne, E Limel, J Wegener and T Buslaps [3] have done their work on investigations on residual stresses in friction still welds. Panagiotis Michaleris [4] has done his work on residual stress distribution for multi-pass welds in pressure vessel and piping components. A welding simulation methodology was implemented and experimentally validated to predict residual stresses on multi-pass welds. The simulation involves performing thermo-elasto-plastic analysis using a consistent element activation approach in the mechanical analysis. A compendium of residual stress distribution in common pressure vessel and piping components was generated by using the multi-pass finite element methodology. Residual stresses were computed for circumferential girth welds on thin and thick walled pipes with various radiuses to thickness ratios. Both single and double V- weld joints were investigated. E. Fridman [5] has developed models for calculating temperatures, distortions and stresses resulting from welding process. The models are implemented in finite element formulation and applied to a longitudinal butt welding. A. Wu, S.Syngellaks and B.G.Mellor[6] have done their work on finite element analysis of residual stresses in a butt weld. A FE simulation of the welding process yielding the welding-induced residual stresses in a butt welded plate was presented. The model was validated by comparison of its predictions with published residual stresses and distortion results from experiments and other numerical simulation. Panagiotis Michaleris and Xin Sun [7] have done their work on finite element analysis of thermal tensioning techniques mitigating weld buckling distortion. A series of finite element simulations and corresponding experiments were performed to demonstrate the technique. Thermocouple measurement was performed to verify the transient thermal analysis and blind hole drilling measurements to verify the predicted residual stresses. Daniel Berglunel [8] has done his work on simulation of welding and stress relief heat treating in the development of aerospace components.

3. FINITE ELEMENT MODELLING PROCEDURE

The process of forming a butt weld that joins two steel plates was simulated. The complete model of the butt weld is shown in fig 1. In this simulation, a 3D finite element analysis was used to simulate the welding process.

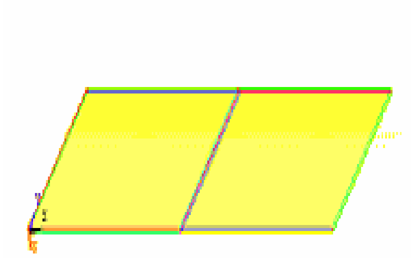

Fig 1 Complete model of butt welded plate

The finite element analysis was carried out in two steps. A non-linear transient thermal analysis was conducted first to obtain the global temperature history generated during the welding process. A stress analysis was then developed with the temperatures obtained from the thermal analysis used as loading to the stress model. The general purpose finite element package ANSYS 5.7 was used for both thermal and stress analysis performed sequentially. The mesh used in the stress analysis was identical to that in the thermal analysis. Fig 2 and Fig 3 show the final mesh map and boundary conditions imposed on the butt welded plate respectively.

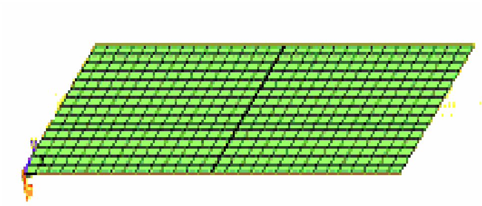

Fig 2 Finite Element Meshing

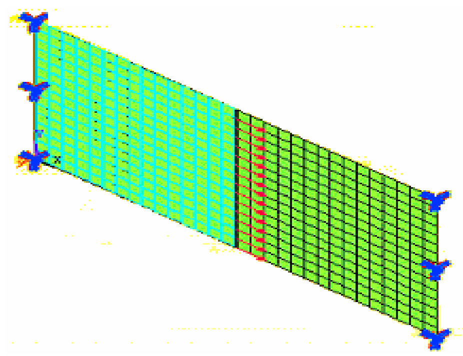

Fig 3 Boundary condition

The material properties of Weld Metal, Base Metal and Heat Effected Zone are both temperature and temperature-history dependent. Due to the lack of information on material properties of weld metal and Heat Effected Zone, both thermal and mechanical properties of Weld Metal and Heat Effected Zone were assumed to be the same as that of the Base Metal in this analysis.

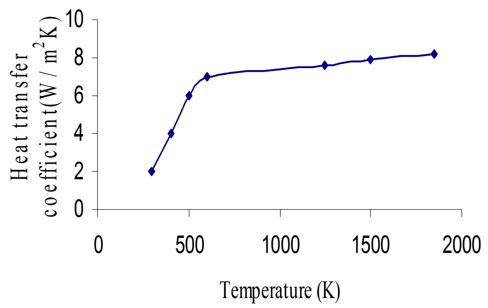

Fig 4 Heat transfer coefficient Vs Temperature
(Thermal property)

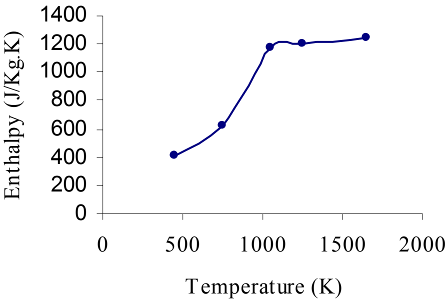

Fig 5 Enthalpy Vs Temperature
(Thermal property)

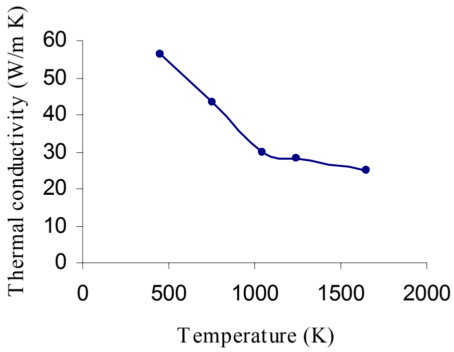

Fig 6 Thermal conductivity Vs Temperature
(Thermal property)

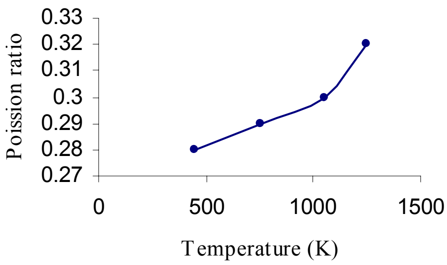

Fig 7 Poisson ratio Vs Temperature
(Mechanical Property)

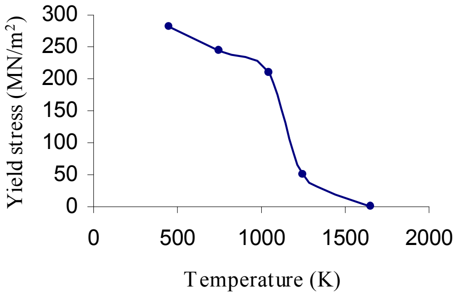

Fig 8 Yield stress Vs Temperature
(Mechanical property)

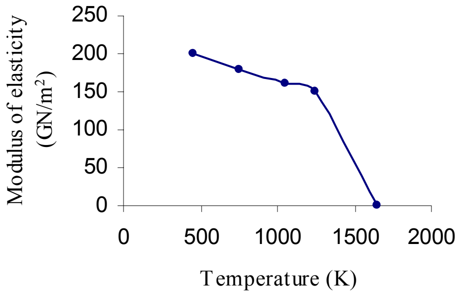

Fig 9 Modulus of Elasticity Vs Temperature
(Mechanical property)

The temperature dependent thermal and mechanical material properties considered are plotted in fig 4 to fig 9. The amount of heat input was found as the product of arc efficiency, voltage and current, which were taken equal to 0.75, 25 V and 210 A respectively in this analysis. The total net heat input was assigned to the weld metal as uniform surface load (20%) and body load (80%).

4. ANALYSIS OF HEAT FLOW

One of the fundamental problems in the analysis of heat flow during welding is how to take into account physical material changes due to temperature changes during the welding process. If the material properties are treated as temperature dependent the equation (1) of heat-flow becomes non-linear,

$$\rho\frac{\partial cT}{\partial t} = Q + \frac{\partial(kx\frac{\partial T}{\partial x})}{\partial x} + \frac{\partial(ky\frac{\partial T}{\partial y})}{\partial y} + \frac{\partial(kz\frac{\partial T}{\partial z})}{\partial z} \qquad (1)$$

Where c is the specific heat, k thermal conductivity, T temperature, Q is the external heat input per unit volume and t is the time. If the material properties are considered temperature independent the equation (specific heat, thermal conductivity do not change with temperature) is reduced to a linear differential equation (2)

$$\rho c\frac{\partial cT}{\partial t} = Q + k\left(\frac{\partial(\frac{\partial T}{\partial x})}{\partial x} + \frac{\partial(\frac{\partial T}{\partial y})}{\partial y} + \frac{\partial(\frac{\partial T}{\partial z})}{\partial z}\right) \qquad (2)$$

In our analysis temperature-dependent thermal properties were assumed, therefore non-linear equations were solved, with all complexity related to their solutions. This assumption was made observing that the temperature changes (gradients) encountered in the Heat Affect Zone are so large that the change of thermal properties could not be neglected. To determine temperatures and other thermal quantities that vary over time there was the need to perform a transient thermal analysis.

To evaluate distortion and residual stress distribution the thermal analysis was performed first in order to find nodal temperatures as a function of time. Once defined temperature history for each node, temperature nodal loads were applied to the structural model. The weld process simulated in a single pass arc welding process. The plate absorbs a part of the heat generated. There are losses from the surfaces in the form of convection and radiation. Therefore to evaluate the amount of heat absorbed by the plate as a portion of the total heat generated the following formula was used

$$Q = \eta VI \quad (3)$$

Where η is arc efficiency, V is the voltage and I the current. The assumptions made are (a) thermal properties, i.e. conductivity, specific heat are temperature dependent. (b) Effects arising from phase change are taken into account, enthalpy changes during the phase change. (c) Heat losses by transfer to the ambient medium are not negligible: convection and radiation is taken into account. Radiation heat losses are accounted by using the equation,

$$q = \varepsilon\, \sigma(T^4 - T\alpha) \quad (4)$$

Where ε is the emissivity of body surface and σ is Stefan-Boltzmann constant, T is the plate temperature and T_α is the ambient temperature. Since heat loss due to radiation varies with the fourth power of the body's absolute temperature, the thermal analysis is highly non-linear. Convection losses are evaluated using the equation (5)

$$q = h(T - T\alpha) \quad (5)$$

Where h is the film convection coefficient, T is the plate temperature and T_α is the ambient temperature.

5. ANALYSIS OF BUTT WELDED PLATE

Consider a 3mm thick flat weldment whose configuration is shown in fig 1. Since the temperature distribution is symmetric about the weld line, only half of the weldment can be modeled. The end of the plate is assumed to be fixed, thus motion is completely restrained in any direction. The transverse bending distortion takes place at the thin weldment. The weldment is completely free to expand and bend in transverse direction. The localized temperature non uniformity yields a variation of shrinkage through the thickness during the cooling down, thus causing the characteristic bending distortion, which are accompanied by a non uniform accumulation of plastic strain in the weld metal and heat affected zones.

In the weld puddle, peak temperatures are higher than the melting temperature. These excessive temperatures arise from relative low value of molten metal conductivity. The cooling curves for weld metal material passing through the liquid-solid phase transition range, in that latent heat liberated as a result of phase transformation Afterward cooling rate decrease during the freezing period.

The incremental elasto-plastic stress and strain analysis was carried out using finite element mesh shown in fig 2. Proper modeling of bending distortion mode in the region in close proximity to the weld centre line remains a relatively fine grid both in the thickness and transverse direction. The initial condition was taken as uniform temperature of 300 K for both plates. The final distorted shape of weldment evaluated when cooling down is completed and temperature is uniform as room temperature value. The maximum distortion of weldment is 0.068 mm.

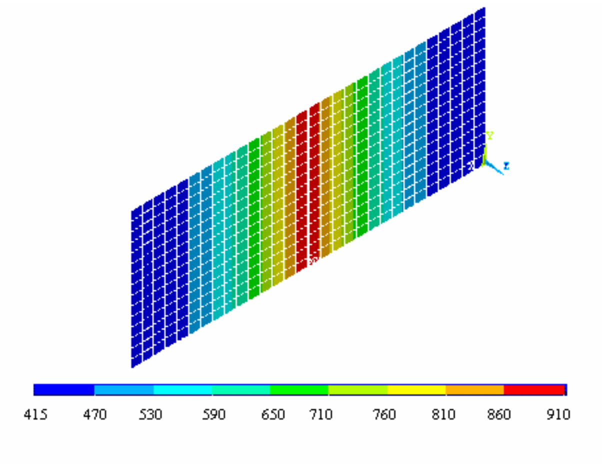

Fig 10 Temperature Analysis at t = 15 sec

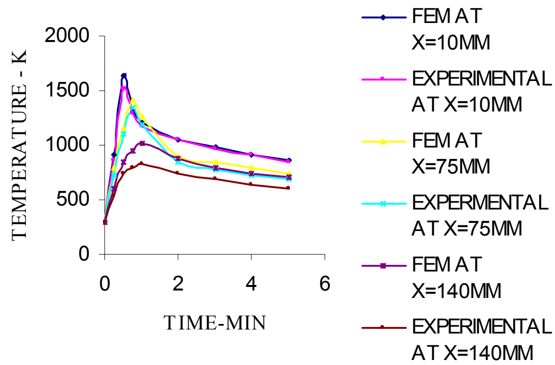

Fig 11 Temperature Vs Time

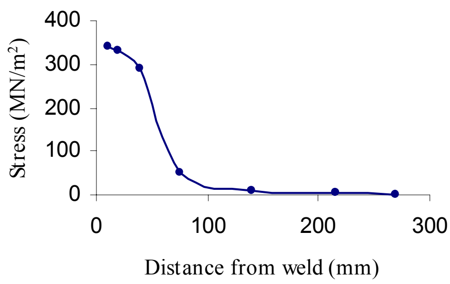

Fig 12 Stress Vs Distance from weld

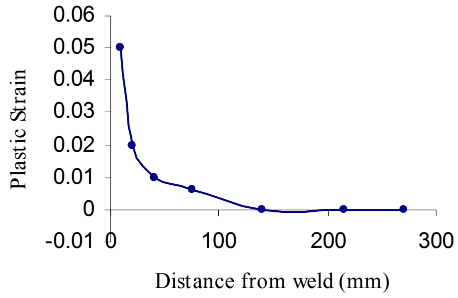

Fig 13 Plastic Strain Vs Distance from weld

Since the displacement of both end of plate was constrained, the unconstraint motion of the weldment in the plane normal to weld line produces transient and residual stress patterns that are dominated by longitudinal stress. Residual stress distribution at final cool down is plotted in fig 12.

The localization of severe temperature gradients in the immediate vicinity of the weld line produces compressive yielding in this region. As more energy is being supplied by the arc and temperature increases, the yield strength quickly decreases until at the melting point, it is negligible. During the time period prior to solidification of weld metal, all material outside the puddle is in compression with that region imidiatly adjacent to the molten zone in the plastic state of stress. Since temperatures in these region are extremely non uniform, the yielding stress very from zero at melting point to about 260 MN/m^2 which is slightly lower than the room temperature yield strength (291 MN/m^2). Plastic deformation in molten material has been completely relived. As cooling down proceeds that portion of weldment that in tension longitudinal stress which are appreciable only in the region within about 75 mm of weld centerline are completely tensile. The tensile stressed in highly stressed region (within the 25mm of centerline)are primarily govern by plastic behavior and region beyond this location is govern by elastic behavior where stress drop off quite rapidly.

In localized region plastic deformation is confined as shown in fig 13, in which residual plastic strain distribution is plotted. With the plastic zone associated With residual stress distribution, plastic strain is grater with in 75 mm of weld centerline. The highest plastic strain levels exist in weld metal and heat affected zone throughout the entire welding cycle, with the exception of the time period in which the weld metal is molten and plastic strain nonexistent. Beyond the heat affected zone plastic strain decreases quit rapidly. The generalized plastic strain, which characterized permanent deformation, may be used as an indicator of cumulative 'damage' in the weld metal and heat affected zones during the welding process. The maximum residual plastic strain exists on the underside of weldment at the weld metal and heat affected zone interface.

6. CONCLUSIONS

The finite element approach has been shown to be a powerful tool both for determining the welding thermal cycle and for evaluating the stresses ad distortions generated as a result of the temperature transients. The analysis procedures are applicable to planer or axisymmetric welds under quasistationary conditions.

The short time thermal response, which yields the dimensions of the fusion and heat affected zones, thus greatly affects the resulting nonuniform shrinkage in these zones. Nonuniform shrinkage in the vicinity of the weld centerline produces the transverse bending distortions typical of these types of welds.

The plastic strains, or permanent deformations, accumulated during welding are maximum at the interface of the weld metal and heat affected zones on the underside of the weldment. With plastic strain as an indicator of 'damage' generated during welding , the analytical prediction that maximum damage occurs in this region is consistent with expected damage in full penetration welds. Thus, in addition to predicting residual stresses and distortions due to welding, the analytical technique can potentially be used for damage assessments as well.

7. REFERENCES

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9. NOMENCLATURE

Symbol	Meaning	Unit
C	Specific heat	(KJ/Kg K)
K	Thermal Conductivity	(W/m K)
h	Heat Transfer Coefficient	(W/ m^2K)
Q	External Heat input	(W)
T	Temperature	(Kelvin)
t	Time	Minute)
ρ	Density	(Kg/m^3)
V	Voltage	(Volt)
I	Current	(Amp)
Tα	Ambient Temperature	(Kelvin)
H	Enthalpy	(J/Kg K)
E	Modulus of elasticity	(GN/ $m^{2)}$
S_y	Yield Stress	(MN/ m^2)
q	Heat flow rate	(J/ sec)
σ	Stefan-Boltzmann constant	(W/ m^2 K^4)
μ	Poisson ratio	
η	Arc Efficiency	
ε	Emissivity	