Residual Stresses in Welding: Some Experimental and Numerical Studies

A Thesis

Submitted in partial fulfilment

For the award of degree of

Doctor of Philosophy

By

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June, 2014

To

My father

APPROVAL OF THE VIVA-VOCE BOARD

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DECLARATION

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c) I have followed the guidelines provided by the Institute in writing the thesis.
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e) Whenever I have used materials (data, theoretical analysis and text) from other sources I have given due credit to the by citing them in the text of the thesis and giving their details in the references.

Date: **(Dhanyamraju V N J Jagannadha Rao)**

ACKNOWLEDGEMENT

I express my deep sense of gratitude to my guide **Prof. K Biswas** for his encouragement and help during the course of my PhD work. He is a strict disciplinarian and kind enough to pardon serious mistakes. My discussions with him in the course of my work are fruitful and giving a good direction to my work. I learnt the art of technical writing under him.

I express my indebtedness to College and Management of **Gayatri Vidya Parishad College of Engineering** for having sponsored me for carrying out PhD work at IIT, Kharagpur under QIP programme.

My profound thanks to **Prof. A K Chattopadhyaya**, **Prof. Ranjan Bhattacharya and Prof. P K. Das** the heads of the department of mechanical Engineering for providing excellent research facilities in the department during my work at Kharagpur.

I express my sincere thanks to **Prof. Subhranshu Roy** the department QIP Research coordinator who is always helped me in clearing official matters.

I express my thanks to my Doctoral Scrutiny Committee members **Prof. Ranjan Bhattacharya, Prof. S. K. Pal and Prof. Partha Saha** for their careful review of my work in various programme seminars. Also I express my thanks to **Bijan Kumar Das** of Central Research Facility at IIT Kharagpur for permitting me to carry out experiments on X-ray diffraction.

Special thanks to **Prof. N R Mandal**, Professor, Department of Ocean Engineering and Naval Architecture for his valuable guidance to write one chapter in this thesis.

Special mention should be made about **Prof. V V Satyamurthi, Prof. D Varadaraju and Prof. K Ramakrishna** for helping me in critical stages of my research work.

I express my thanks to my peer research workers **Debashish Khan, Nikhil Agarwal, Mangam Venu, Panduranga, Chandra Mouli and Negi** for sharing sorrows and joys of this research work.

Further I must thank **Maniram Chakraborty** and **Avipshu Bhattacharya** of welding Lab for helping me in carrying out experiments.

I must express sincere thanks to my mother **Smt. D Subhadra Devi** and wife **Smt. D V VLakshmi** who looked after me and my family carefully when I was completely engaged in the research work. Further I express my indebtedness to my father in law **Sri N Prabhakara Rao** who did a yeoman service and gave elderly advices during the course of research work. Also I express my indebtedness to my uncle **D Bala Krishna Murthy** who is source of encouragement in all my academic pursuits.

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ABSTRACT

The intense localized heating and cooling in the fabrication of welded joints leads to residual stresses and distortion which reduce the service life of the joint. The prediction and mitigation of residual stresses is as important task in the design and fabrication of the joint. Prediction of residual stresses requires solution to a non-linear transient thermo-elasto-plastic problem. The complicated physics of welding include material dependence on temperature, phase change, plasticity, filler metal addition and restraint.

In this work thermo-mechanical analyses of various welded components namely a square corner joint, butt welded plates, a tee panel, bead on pipe and spiral welded pipe are presented. The materials used are mild steel and C-Mn steel. Weld bead is modelled as circular arc with the initial temperature of the filler metal is at its melting temperature. Double ellipsoidal heat flux density distribution is used to model the heat input and filler element additions are made by element birth-death method in a transient thermal solution based on enthalpy. Rate independent kinematic hardening is used to model the plastic behaviour and the thermal load is calculated with the reference temperature of the base metal is at ambient temperature and that of filler metal is at melting temperature. The mechanical strains elastic strains and plastic strains are omitted from the analyses when the temperature of the metal is at or above the melting temperature.

Numerical solutions are obtained for temperature and residual stresses. Thermal histories at various locations of the welded components are measured with online thermocouple measurements and residual stresses at various locations of square corner joint and pipe are measured by X-ray diffraction. The comparison of computed thermal histories with experimental thermal histories yielded very good agreements. Experimental values of residual stresses are compared with the corresponding results of computed results. In bead on pipe welding both the hardening methods kinematic and isotropic hardening models resulted in almost identical values of residual stress distributions. Thermal histories and residual stresses of a typical spiral welded pipe are also presented. Further the effect of weld pass sequencing on residual stresses is investigated with weld pass sequencing methods skip step, back step and normal weld pass sequencing methods. There is a good amount of reduction in the values of residual stresses and distortion with nonconventional weld pass sequencing methods with skip step weld pass sequencing offering least amount of residual stresses and distortion.

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LIST OF SYMBOLS

Double ellipsoidal heat source

a, b, c1, c2 are the parameters of the heat source in mm and $fr+f_f = 1$

a_f *= Front Ellipsoidal semi-axes length (mm)*

a_r *= Rear Ellipsoidal semi-axes length (mm)*

b = Half width of arc (mm)

c = Depth of arc (mm)

f_f *= Distribution factor in the forward direction of welding*

f_r *= Distribution factor in the rear direction of welding*

I = Current (A)

Q = Heat input (W/m^2)

q = Heat flux density in W/m^3

q_f *= Power density in front Ellipsoid* (W/mm^3)

q_r *= Power density in rear Ellipsoid* (W/mm^3)

R_o*= Pipe outer radius (mm)*

r = Radius of pipe (mm)

r = Distance from centre of the arc in mm

$\bar{r}$ *= Radius of arc in mm.*

t = Time in sec

V = Voltage (V)

v = Welding speed in mm/sec

z = *Distances from the torch centre in axial direction (mm)*

η = *Efficiency of welding*

θ = *Angle from instantaneous arc position (radian)*

Heat transfer coefficients

$C_p = specific\ heat\ J/kgK$

D = *diameter of the cylinder (m)*

Gr_L = = *Grashoff number*

h = *Heat transfer coefficient* (W/m^2K)

g = *Acceleration due to gravity* (m/s^2)

$k = coefficient\ of\ thermal\ conductivity\ W/mK$

L = *length of the plate (m)*

x, y, z = *Cartesian co-ordinates*

$\overline{Nu_L}$ = *Average Nusselt number*

n_λ = *thermal conductivity parameter*

n_μ = *viscosity parameter*

$\Pr$ = *Prandtl number*

r, θ, z = *Cylindrical co-ordinates*

T_f = *Temperature of the film (K)*

T_s = *Temperature of the plate* (^0C)

T_∞ = Ambient temperature (^0C)

β = Volumetric coefficient of thermal expansion (1/K)

η = dimensionless similarity coordinate variable

θ = dimensionless temperature variable

ט = Kinematic viscosity (m^2/s)

ρ= density kg/m^3

FEM formulation

$[B] = strain\ displacement\ matrix$

$[C] = heat\ capacity\ matrix$

$[D] = elasticity\ matrix$

$[D]_s^{ep} = elasto - plastic\ tangent\ matrix$

$\{\Delta d\} = incremental\ displacement$

$F_{12} = shape\ factor$

$\{F\}_n = external\ load$

$\{f\} = load\ vector$

$\{f\}_n = internal\ load$

$\{f_P\} = point\ load\ vector$

$\{f_{th}\} = thermal\ load\ vector$

$\{f_w\} = body\ force\ vector$

$\{f_{\epsilon 0}\} = initial\ strain\ vector\ load$

$\{f_{\sigma 0}\} = initial\ stress\ vector\ load$

$H = enthalpy$

$h = heat\ transfer\ coefficient\ W/m^2K$

$[K] = stiffness\ matrix, conductivity\ matrix$

$[K]_n^{tan} = tangent\ stiffness\ matrix\ at\ n\ iteration$

$[N] = shape\ function\ matrix$

$\{R\}_n^i = residual\ at\ i^{th}\ iteration$

$\| R \| = convergence\ norm$

$S = surface\ area\ m^2$

$T = temperature\ \ {}^0C$

$\{T\} = temperature\ vector$

$\{T\} = traction\ force\ vector$

$V = volume\ m^3$

Γ = *boundary*

$\{\delta\} = displacement\ vector$

$\epsilon = emmisivity$

$\epsilon = convergence\ criterion, strain$

$\{\epsilon\} = total\ strain\ vector$

$\{\epsilon^e\} = elastic\ strain\ vector$

$\{\epsilon^p\} = plastic\ strain\ vector$

$\{\epsilon^{th}\} = thermal\ strain\ vector$

$\{\epsilon^{ph}\} = phase\ transformation\ strain\ vector$

$\sigma = stefen\ boltzman's\ constant$

$\{\sigma\} = stress\ vector$

$\{\sigma_e\} = elastic\ stress\ vector$

$\{\sigma_0\} = initial\ stress\ vector$

$\Omega = domain$

Radial Return Method

$E = elastic\ modulus$

$F_n = yield\ surface$

$G = shear\ modulus$

$I = second\ order\ identity\ tensor$

$k = bulk\ modulus$

$tr = trace$

$\epsilon^d = deviotoric\ strain$

$\epsilon^e = elastic\ strain$

$\epsilon^h = hydrostatic\ strain$

$\epsilon^p = plastic\ strain$

$\epsilon_x, \epsilon_y, \epsilon_z = normal\ components\ of\ strains$

$\bar{\epsilon} = effective\ strain$

$\mu = elastic\ constant$

$\upsilon = poisson's\ ratio$

$\sigma =$ stress

$\sigma^d =$ deviotoric stress

$\sigma^h =$ hydrostatic stress

$\sigma_{x\,,}\sigma_{y,}\sigma_z =$ normal components of stressses

$\sigma_y =$ yield stress

$\bar{\sigma} =$ effective stress

$\sigma_n^* =$ trial elastic stress at iteration n

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LIST OF PUBLICATIONS FROM PRESENT RESEARCH

1. Jagannadha Rao D V N J and Biswas K. (2007). Temperature distribution in a welded corner joint: FEM prediction and its experimental verification. *Proceedings of International Conference on Advances in Manufacturing Technology*, Durgapur.
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