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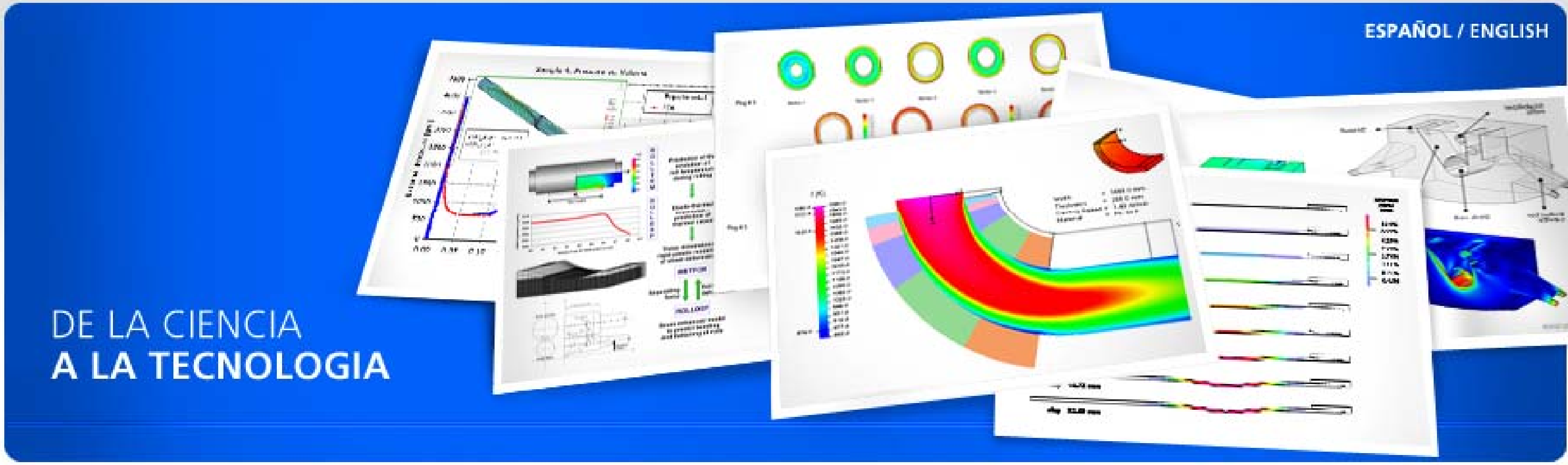

Thermo – Mechanical Problems

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Agenda

- Thermo-elastic material model
- Thermo-elastoplastic material model
- Finite elements in thermo-mechanical problems
- Material properties for modeling welding processes

Thermo - elasticity

Using, for example, the Green-Lagrange strain tensor; and ${}^tT$ being the temperature, we can write for any particle in the spatial configuration its internal energy per unit mass (elastic energy + caloric energy) as

$$ {}^t\mathrm{U} = {}^t\mathrm{U}\left({}^t_\circ\underline{\underline{\varepsilon}}, {}^tT\right) \qquad (5.112a) $$

and considering a *reversible process* (Boley & Weiner 1960), we can write

$$ {}^t\eta = {}^t\eta\left({}^t_\circ\underline{\underline{\varepsilon}}, {}^tT\right) \qquad (5.112b) $$

where ${}^t\eta$ is the spatial *entropy per unit mass.*

The principle of energy conservation (First Law of Thermodynamics) can be written as

$$ \frac{D\,{}^t\mathrm{U}}{Dt} = \frac{1}{{}^\circ\rho}\,{}^t_\circ\underline{\underline{\mathbf{S}}} : {}^t_\circ\dot{\underline{\underline{\varepsilon}}} + {}^tT\ {}^t\dot{\eta}\ . \qquad (5.113) $$

Thermo - elasticity

Small strains and small temperature increments

$$ {}^{t}\sigma_{\alpha\beta} = \lambda\, \delta_{\alpha\beta}\, {}^{t}\varepsilon_{\gamma\gamma} + 2\, G\, {}^{t}\varepsilon_{\alpha\beta} - \frac{E\, \alpha}{(1-2\nu)} \left({}^{t}T - T_{R} \right) \delta_{\alpha\beta} $$

For the heat transfer equation

$$ k\, \nabla^{2\,t}T = \frac{{}^{t}T\, E\, \alpha}{(1-2\nu)}\, {}^{t}\dot{\varepsilon}_{\alpha\alpha} + {}^{\circ}\rho\, {}^{t}c\, {}^{t}\dot{T}\ . $$

Coupled Problems

In (Boley & Weiner 1960) numerical examples in aluminum and steel were considered and it was shown that the coupling is negligible when

$$\frac{{}^t\dot{\varepsilon}_{\alpha\alpha}}{3\,\alpha\,{}^t\dot{T}} \ll 20\,. \qquad (5.126)$$

Sequential solution

Solve thermal problem and get T-distribution

↓

Using T-distribution and temperature dependent material properties solve the mechanical problem

Thermo – elasto - plasticity

For infinitesimal strains we use the standard decomposition:

$$ {}^{t}\underline{\underline{\mathbf{d}}} = {}^{t}\underline{\underline{\mathbf{d}}}^{E} + {}^{t}\underline{\underline{\mathbf{d}}}^{P} + {}^{t}\underline{\underline{\mathbf{d}}}^{TH} $$

The yield function:

$$ {}^{t}f\left({}^{t}\underline{\underline{\sigma}} \, , \; {}^{t}q_{i} \;\; i=1,n \, , \; {}^{t}T \right) = 0 $$

Thermo – elasto - plasticity

Von Mises with isotropic hardening:

$$ {}^t f = \frac{1}{2}\, {}^t\underline{\underline{s}} : {}^t\underline{\underline{s}} - \frac{{}^t\sigma_y^2}{3} = 0 $$

$$ {}^t\sigma_y = {}^t\sigma_y \left({}^t\bar{\varepsilon}^P ,\ {}^tT \right) $$

Von Mises with kinematic hardening:

$$ {}^t f = \frac{1}{2} \left({}^t\underline{\underline{s}} - {}^t\underline{\underline{\alpha}} \right) : \left({}^t\underline{\underline{s}} - {}^t\underline{\underline{\alpha}} \right) - \frac{{}^t\sigma_y^2}{3} $$

$$ {}^t\sigma_y = {}^t\sigma_y \left({}^tT \right);\ {}^t\alpha_{ij} = \int_0^t {}^\tau\dot{\alpha}_{ij}\, d\tau;\ \text{and},\ {}^t\dot{\alpha}_{ij} = {}^tc\left({}^tT\right)\ {}^td_{ij}^P $$

Thermo – elasto - plasticity

For the unstressed state with no previously accumulated plastic strains (Boley & Weiner 1960)

$$ {}^t f(\underline{\underline{0}}, 0, {}^t T) < 0 \ . \qquad (5.130) $$

During plastic loading the *consistency equation* takes the form (Boley & Weiner 1960),

$$ \dot{f} = \frac{\partial^t f}{\partial^t s^{ij}} \, \dot{s}^{ij} + \frac{\partial^t f}{\partial^t \varepsilon^P_{ij}} \, {}^t d^P_{ij} + \frac{\partial^t f}{\partial^t T} \, {}^t\dot{T} = 0 \ . \qquad (5.131) $$

σ-ε-T relations

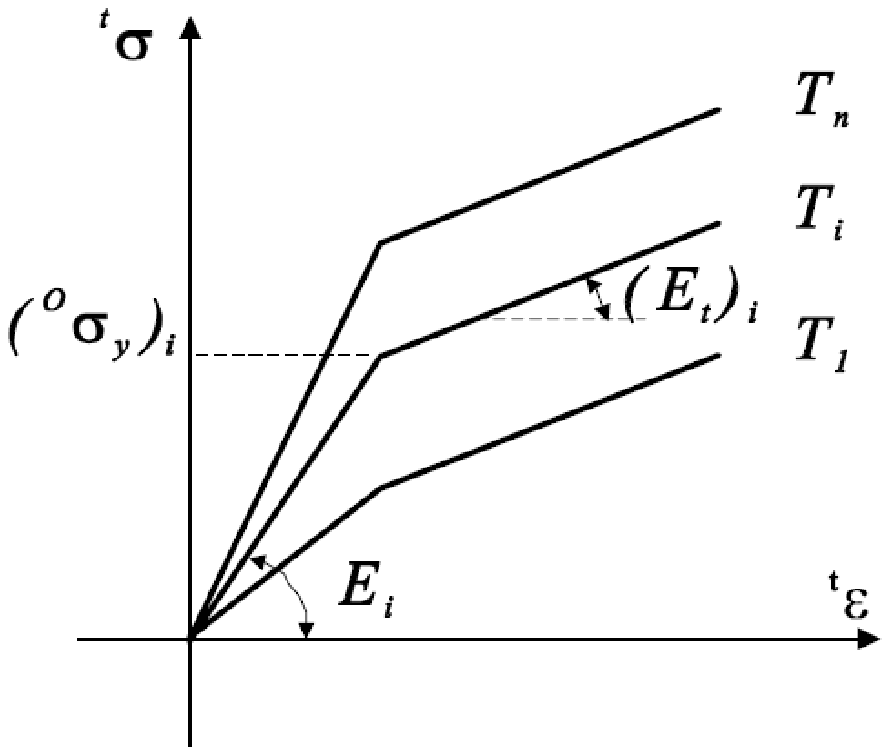


Fig. 5.11. Stress-strain curves at different temperatures, T_i

Coupled problems

If the heat generated by the plastic dissipation is neglected

Sequential solution

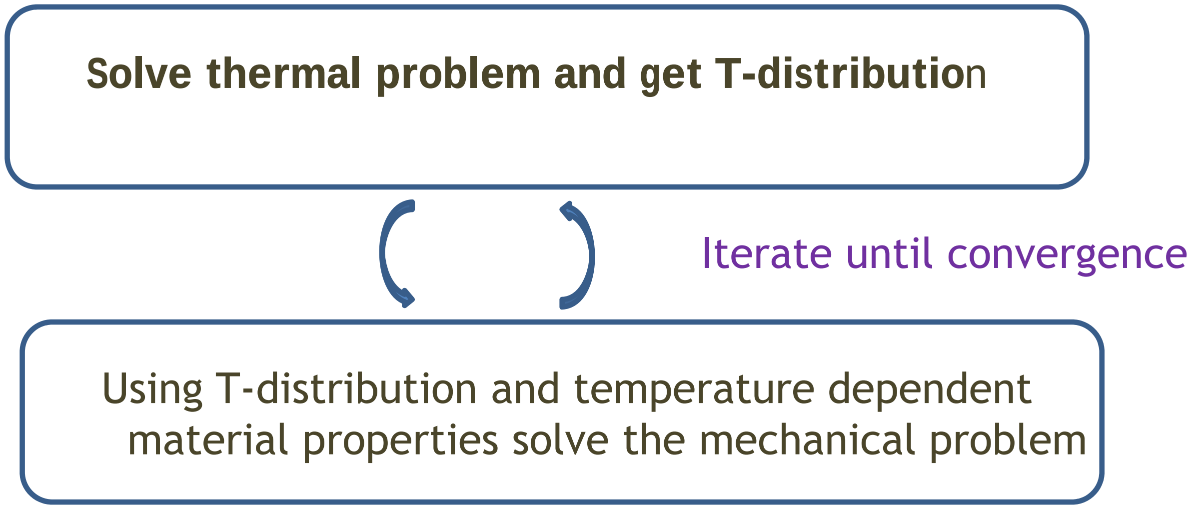
Solve thermal problem and get T-distribution

↓

Using T-distribution and temperature dependent material properties solve the mechanical problem

Coupled problems

Considering the heat generated by the plastic dissipation



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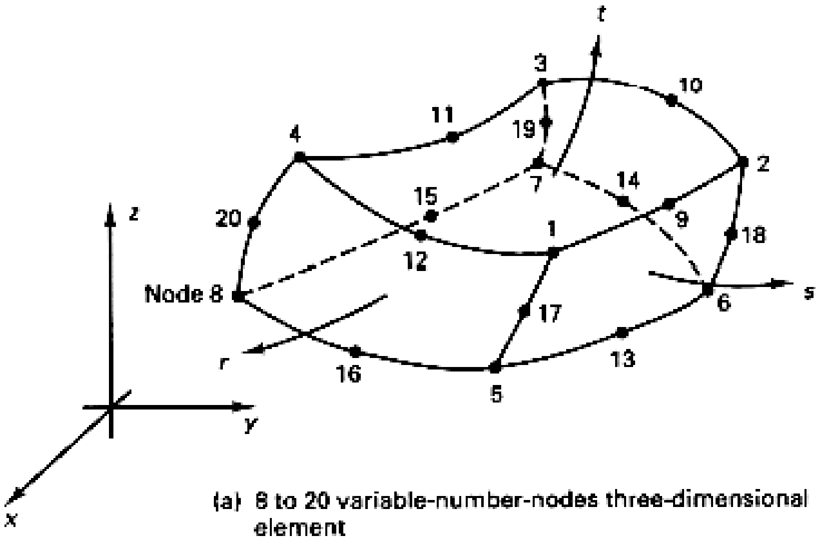
Finite elements in thermo – mechanical problems

Using isoparametric elements

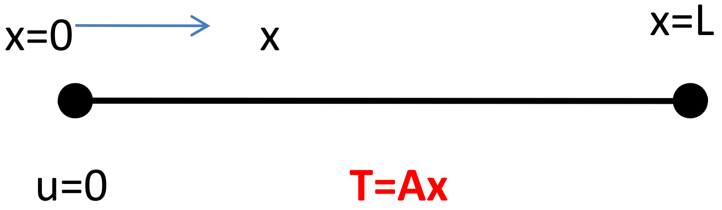


(a) 8 to 20 variable-number-nodes three-dimensional element

Figure 5.5 Interpolation functions of eight to twenty variable-number-nodes three-dimensional element

$$
\begin{aligned}
x_i(r,s,t) &= h_k(r,s,t)\, x_i^k \\
u_i(r,s,t) &= h_k(r,s,t)\, u_i^k \\
T_i(r,s,t) &= h_k(r,s,t)\, T_k
\end{aligned}
$$

Sample example



$$
\begin{aligned}
u &= \hat{u}\frac{x}{L} \\
\sigma &= E\left(\frac{\hat{u}}{L} - \frac{Ax}{L}\right)
\end{aligned}
$$

Cannot represent the correct solution σ=0
I need to have the same interpolation for ε and T

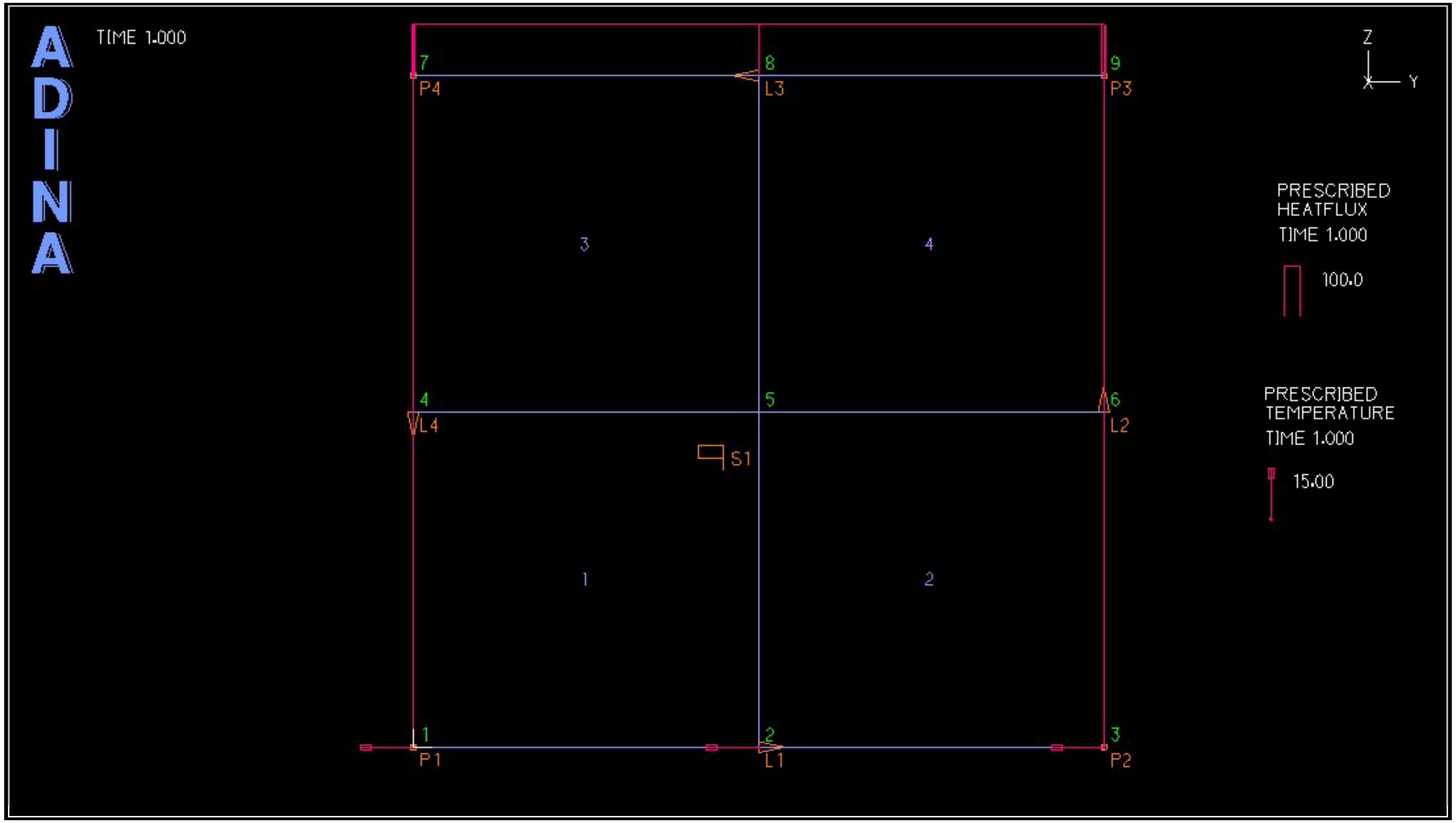
Therefore I need a displacement interpolation order higher than the temperature interpolation order

Example # 1 – Steady State

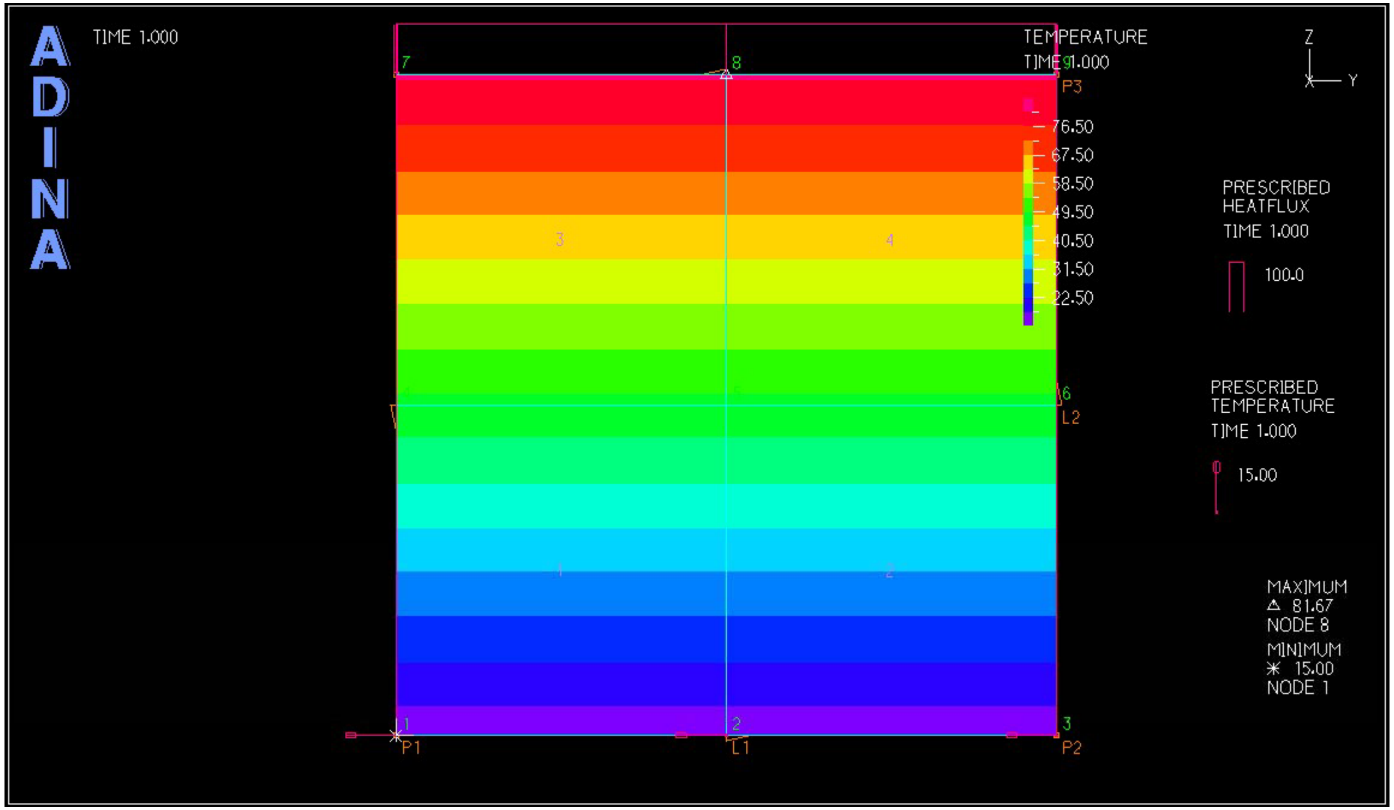
Material properties

Thermal properties	Mechanical properties
k=15	E=10,000
	v=0.0
	A=0.001

Example # 1 – Steady State

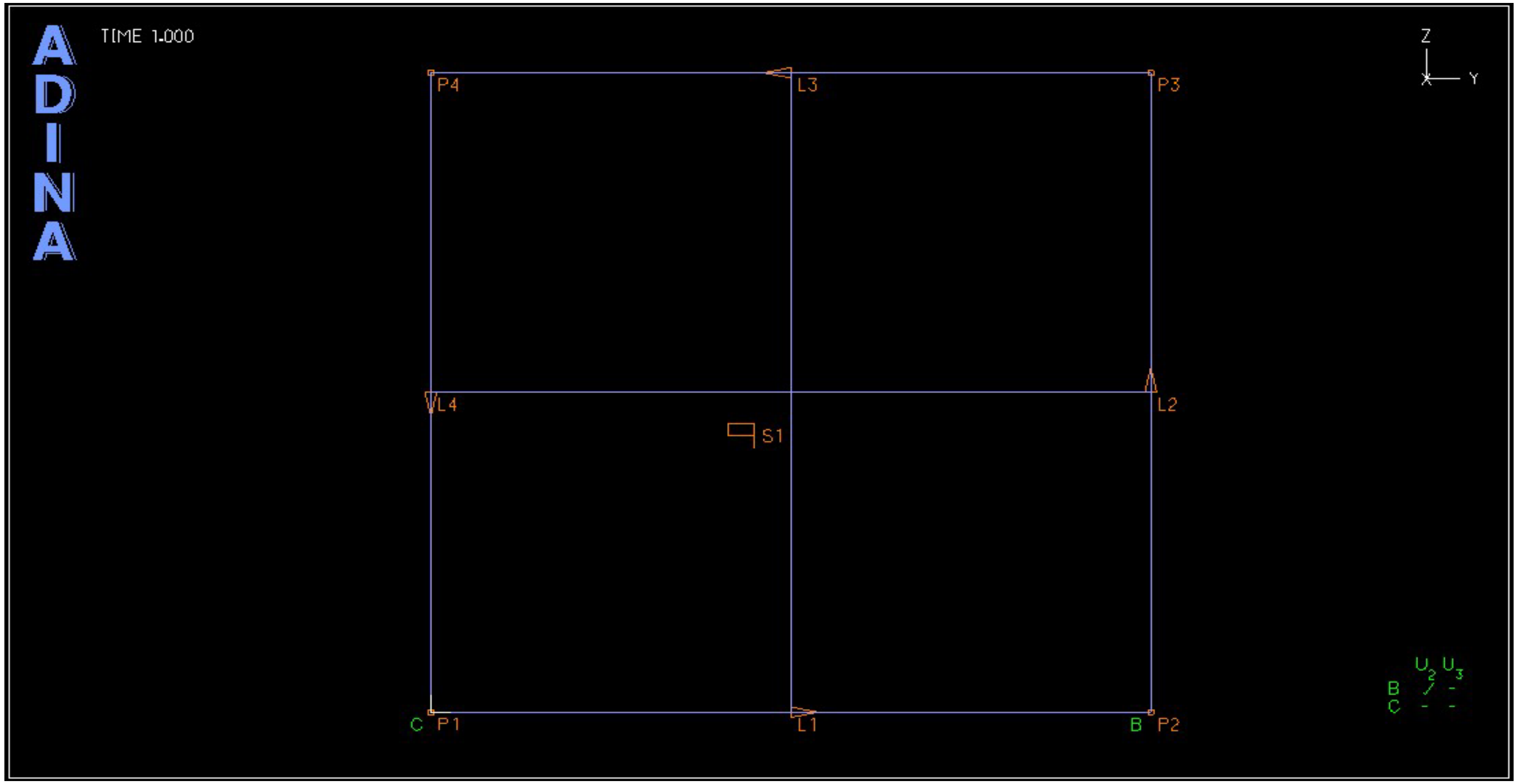


Example # 1 – Steady State

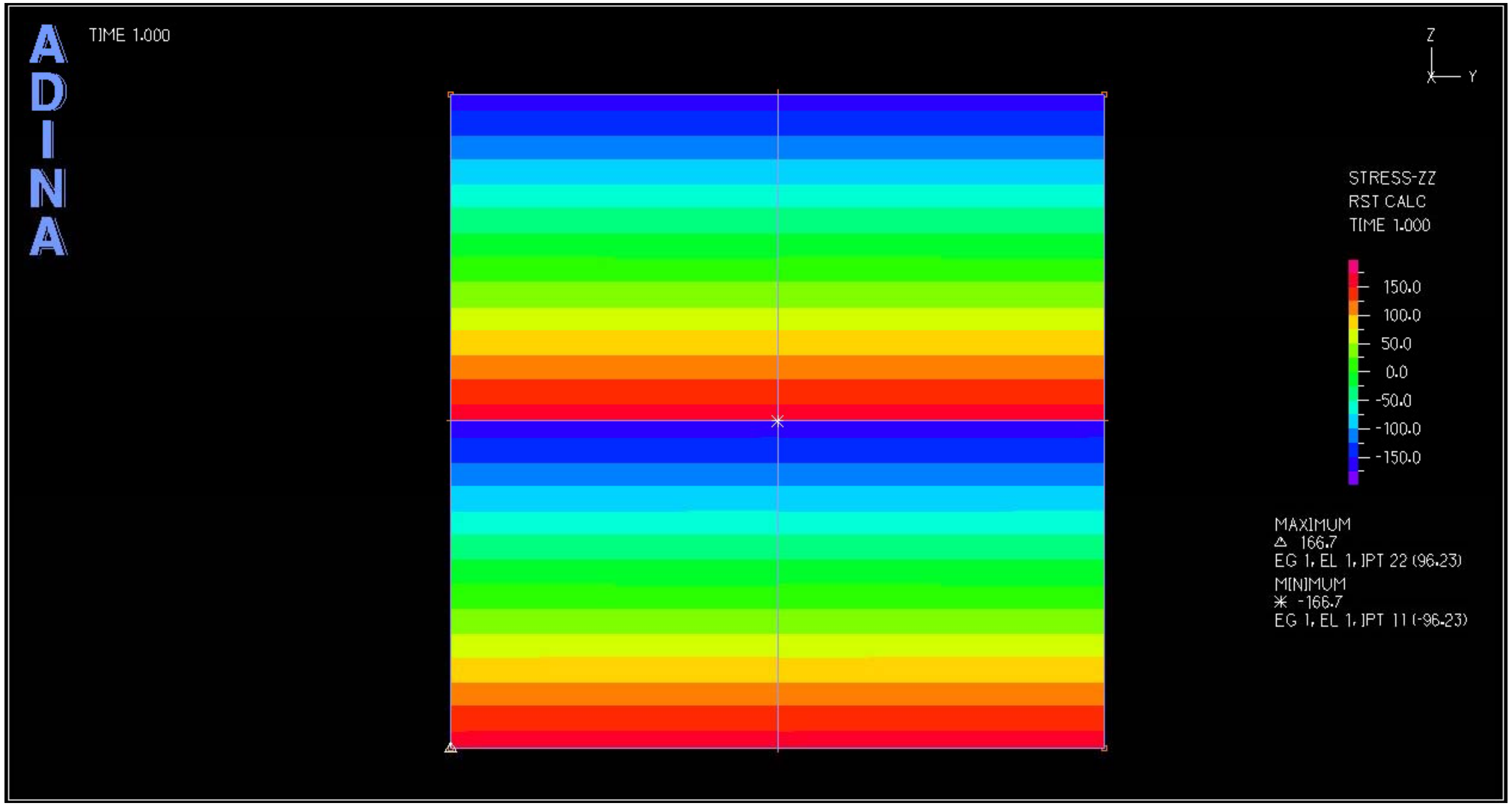


Exact linear temperature distribution

Example # 1 – Steady State



Example # 1 – Steady State



BAD RESULT

Example # 1 – Steady State

The reason for the bad result is:

- Temperature interpolation: bi-linear
- Displacement interpolation: bilinear; hence strain interpolation less than bilinear

$\sigma=0$ cannot be fulfilled

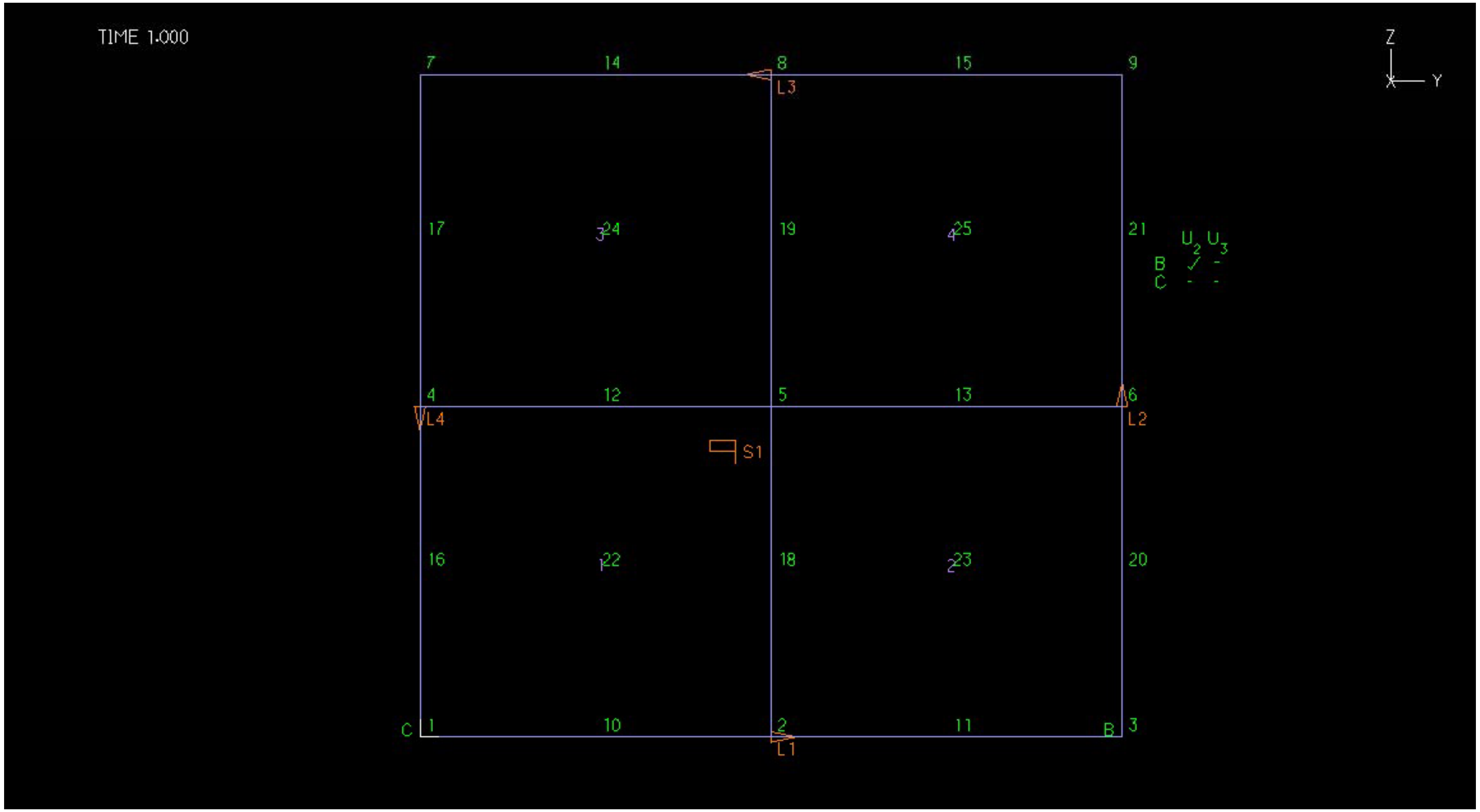
Example # 1 – Steady State

Try using 4N for thermal analysis

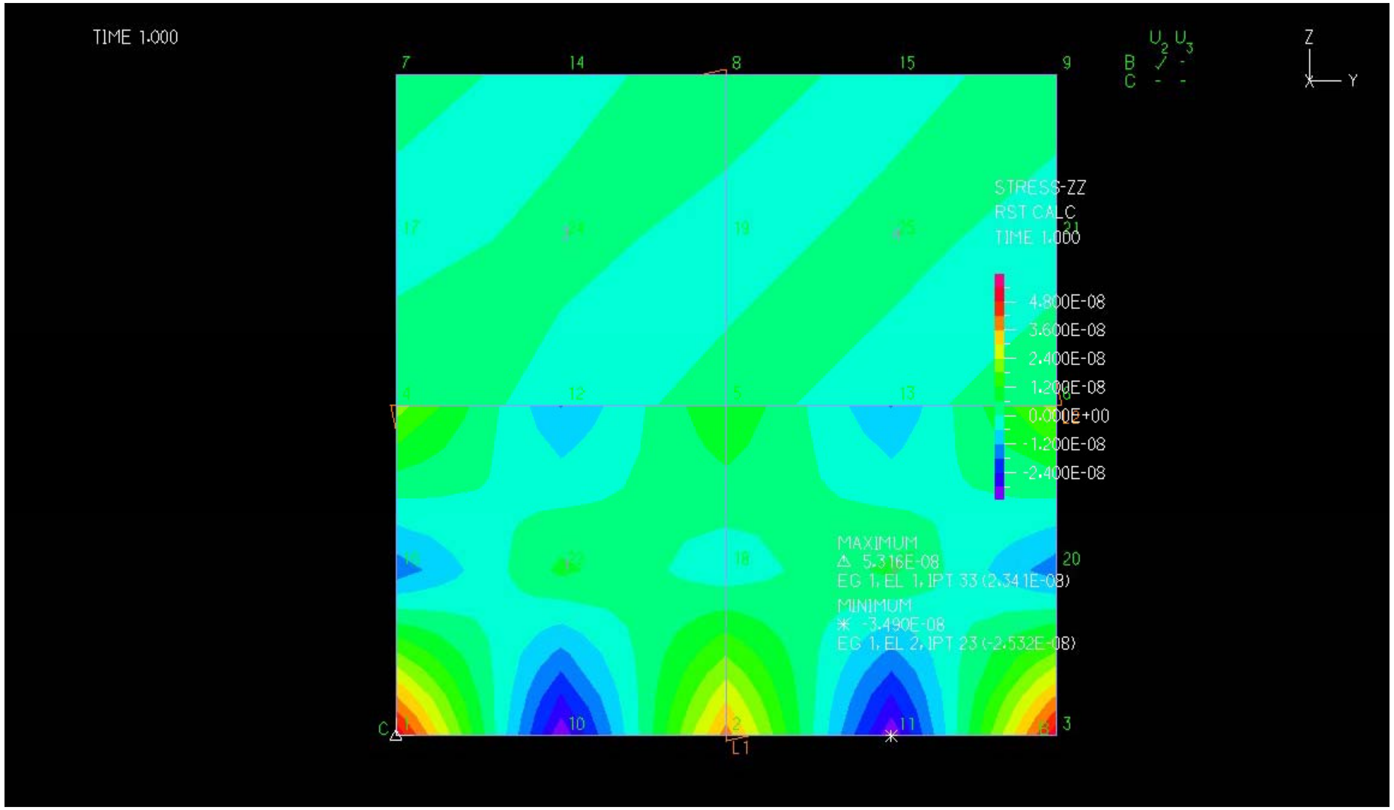
and

9N for mechanical analysis

Example # 1 – Steady State

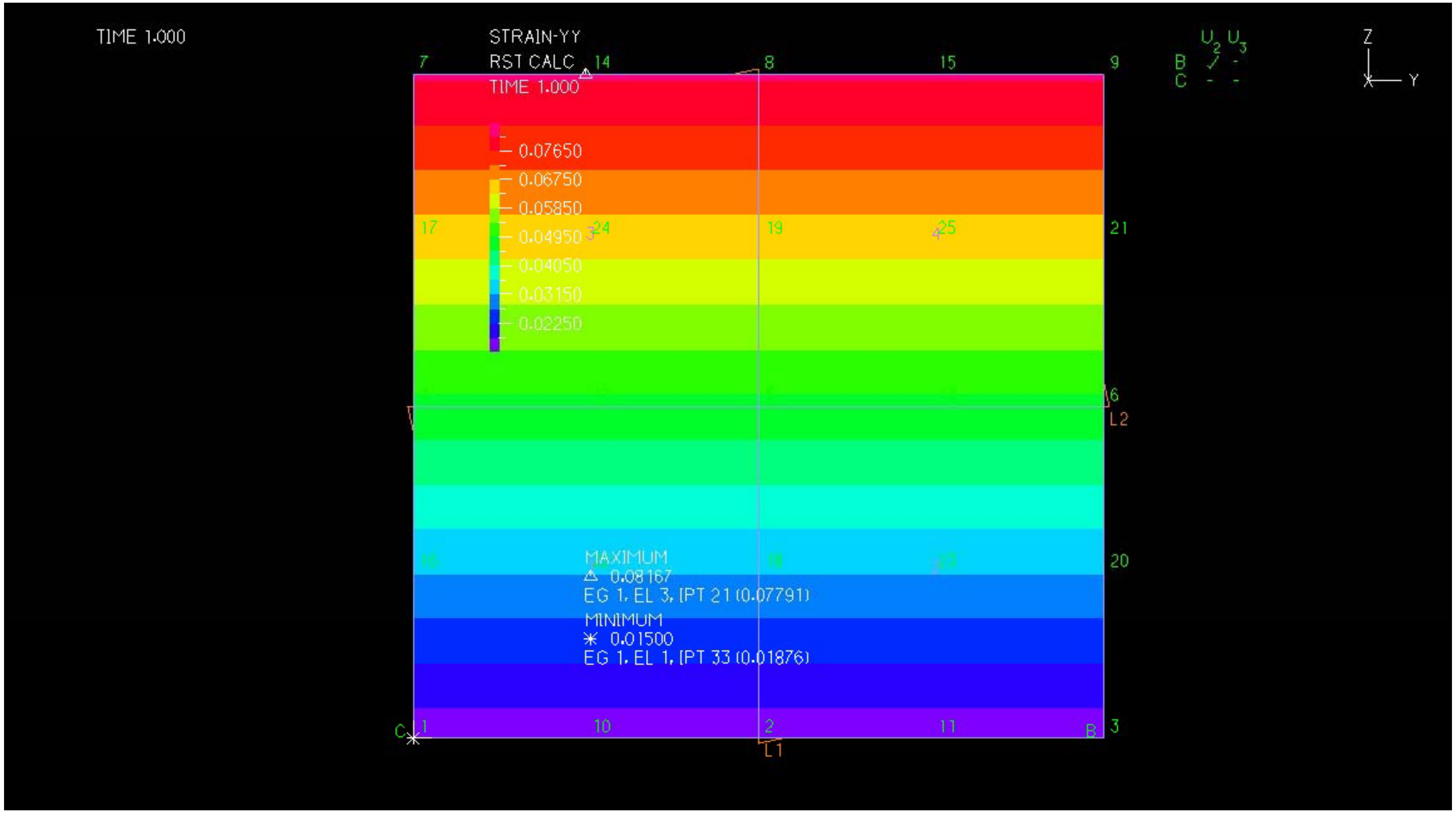


Example # 1 – Steady State

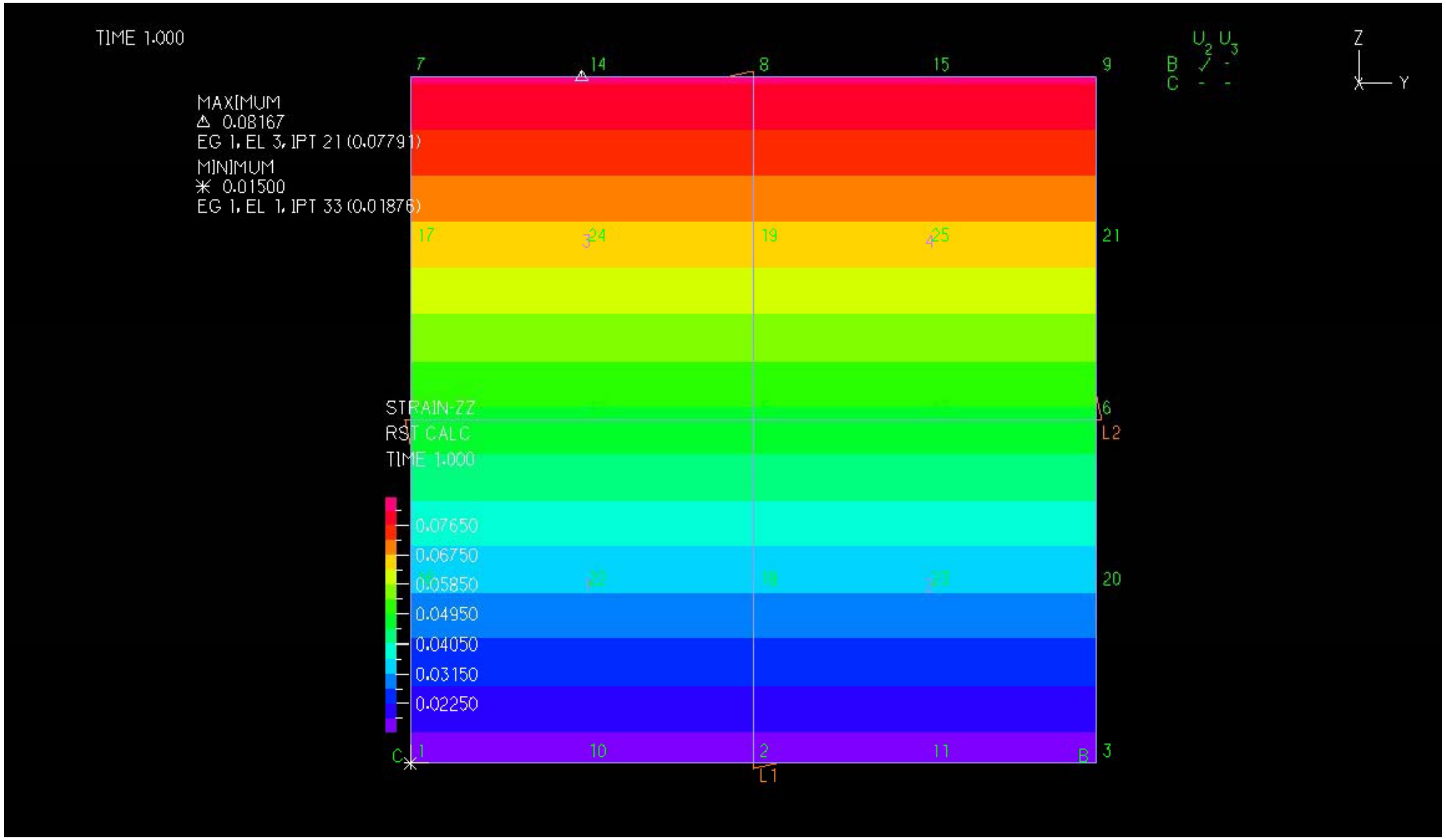


Exact result

Example # 1 – Steady State



Example # 1 – Steady State



Welding Processes

Sequential solution

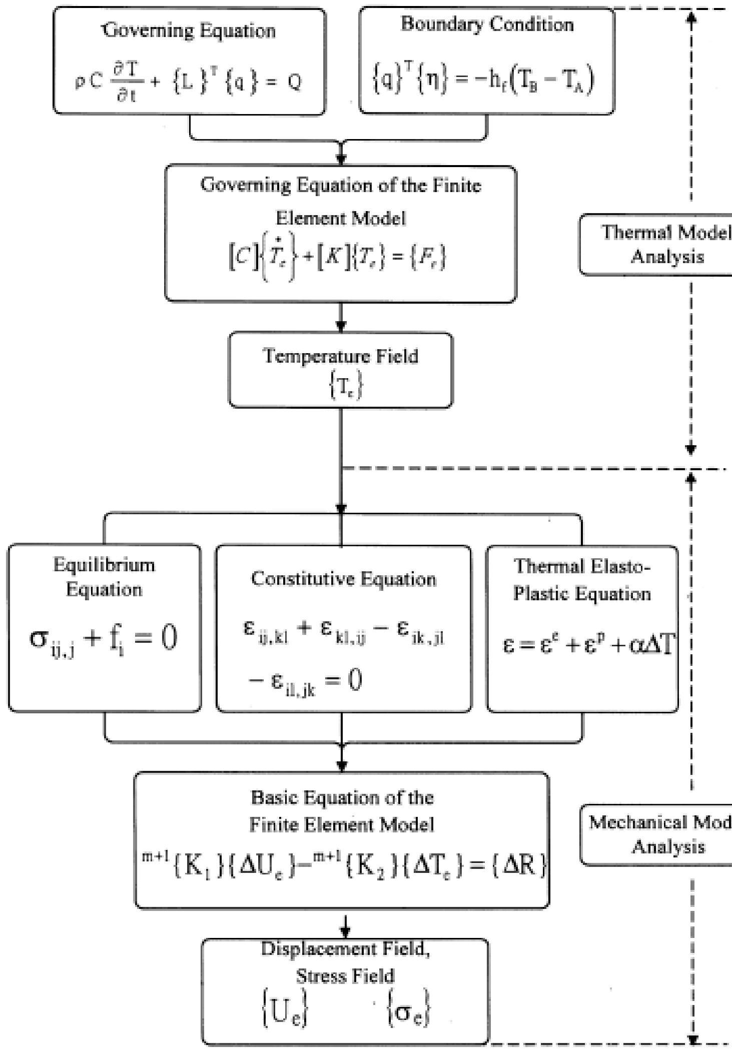


Fig. 1. The analysis procedures for the thermo-mechanical couple field.

Teng-Chang, IJPVP, 1998

SAW multipass butt welding

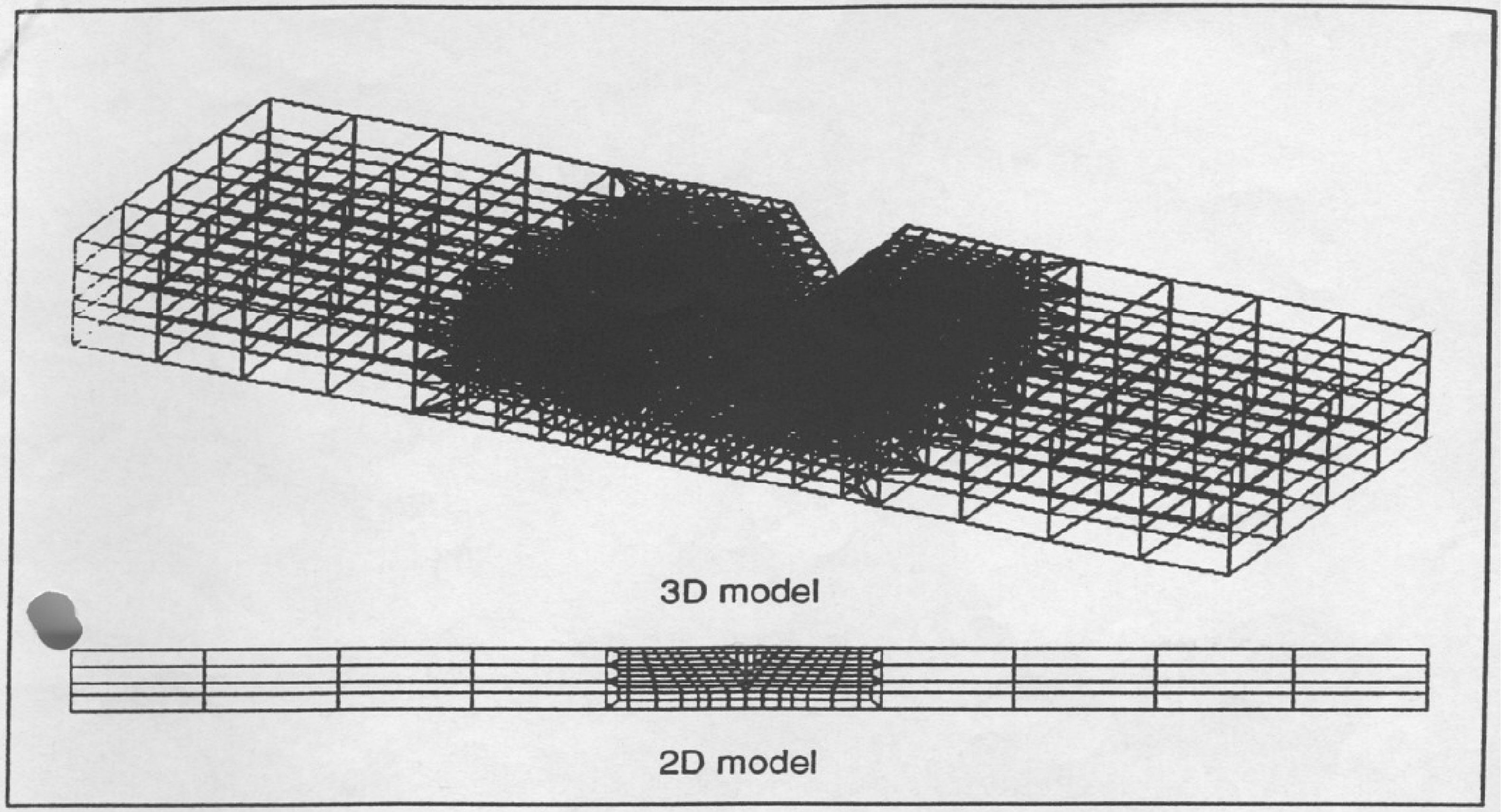


Figure 1: 3D and 2D meshes used in the analyses

SAW multipass butt welding

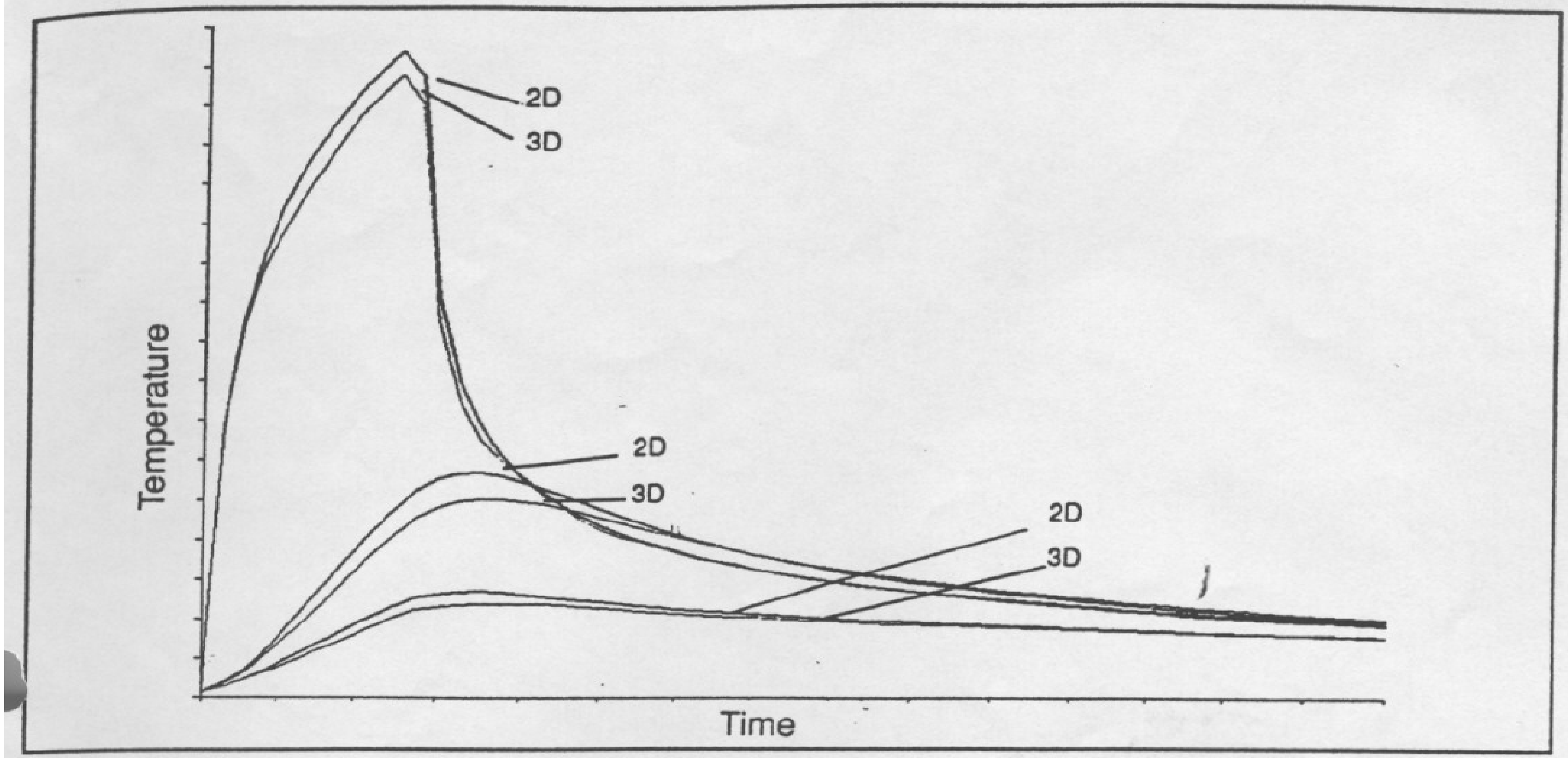


Figura 2:Thermal cycles predicted with 2D and 3D FEM models at points A,B and C (see Fig.3) during a single pass weldment.

SAW multipass butt welding

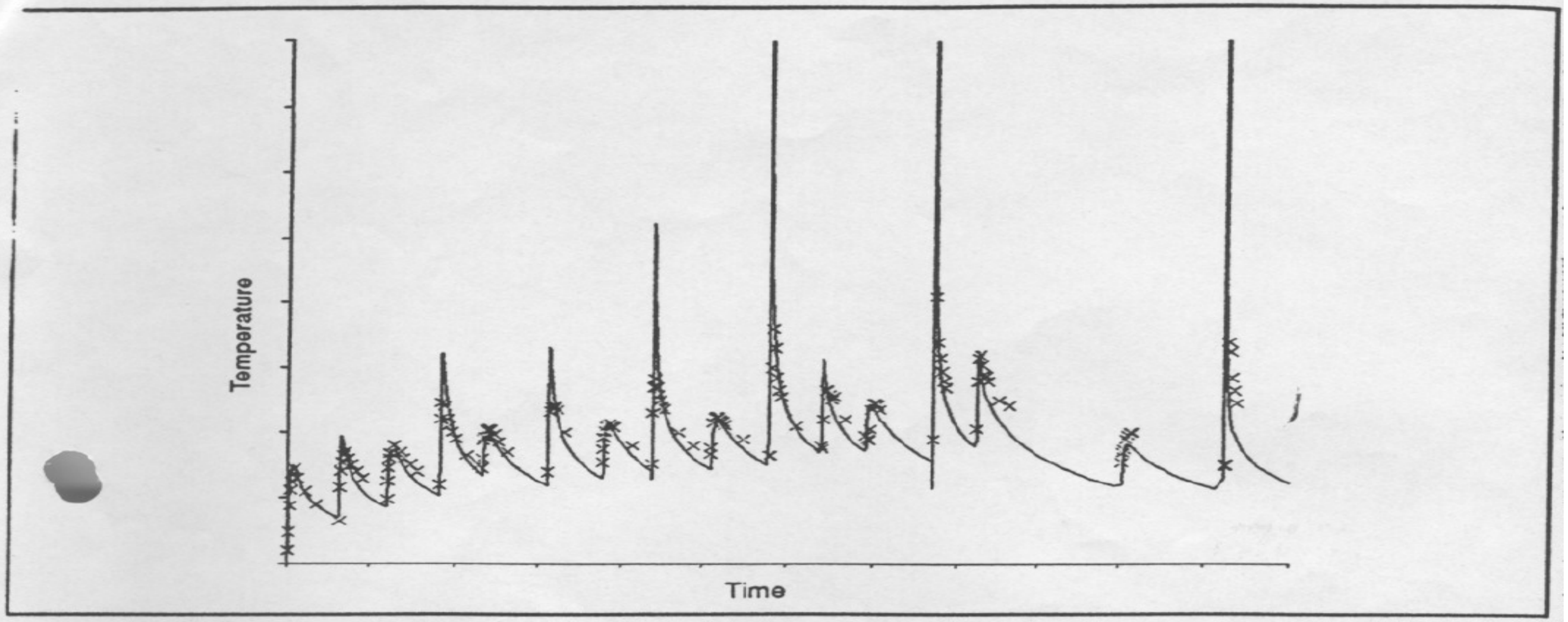


Figure 4a Measured temperatures at point D compared with FEM results

I = 425/450 A
V = 28/29 Volt
v = 48/50 cm/min
resulting a heat input:
HI= 1.4/1.6 KJ/mm

A very good agreement is observed.

It is important to note that similar thermal cycles in corresponding points along the weld line confirm our assumption of a 2D model.

SAW multipass butt welding

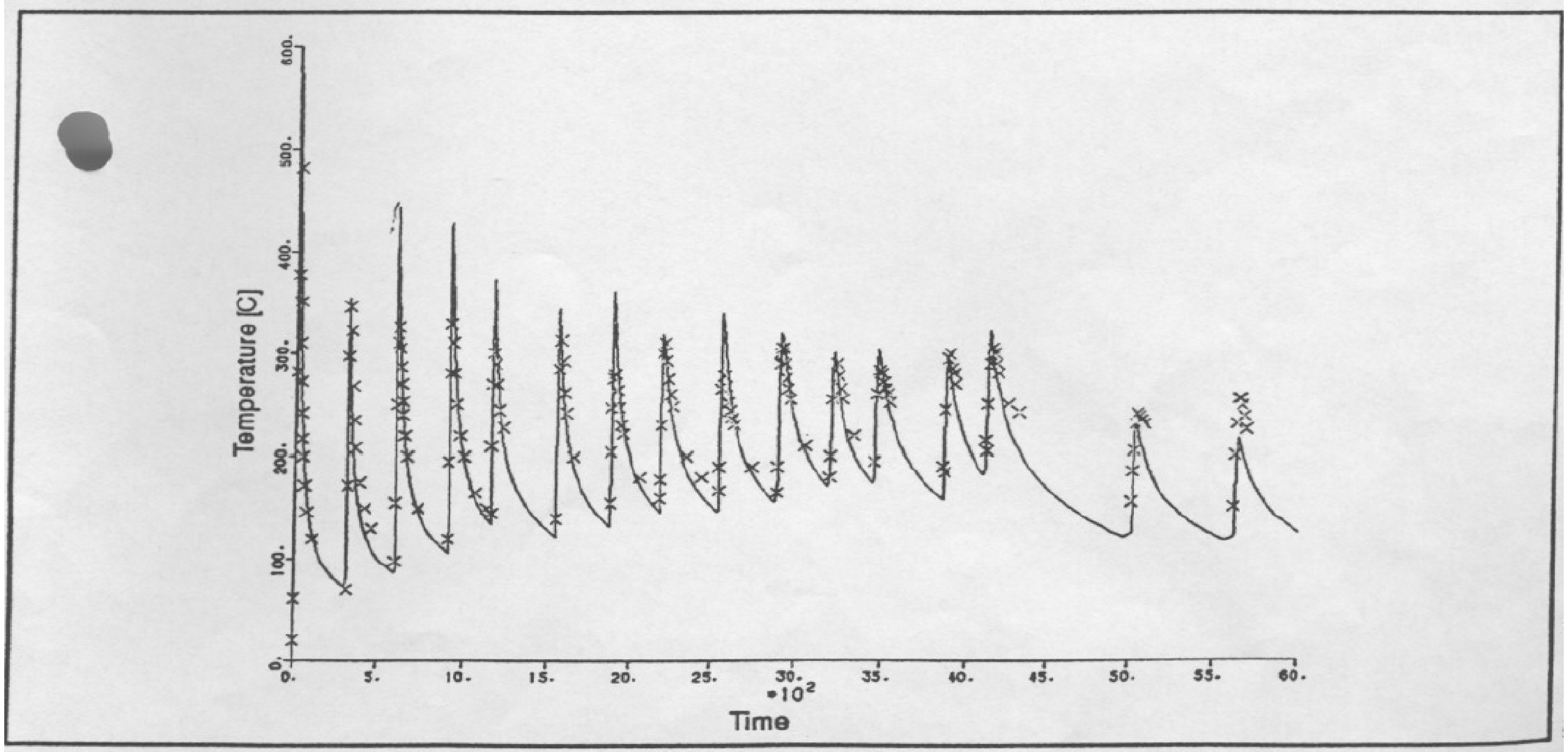


Figure 4b Measured temperatures at point B compared with FEM results

SAW multipass butt welding

Thermal material properties

Table I - Thermal Properties.
Adopted convection coefficient h=48e-4 W/mm2C

Ref.	Conduct."k"[W/m C]	Spec. Heat "ρc" [J/mm3 C]	Latent Heat
[1]	3D: 25 2D: 40	ρc=ρc (θ) 0.005-0.010	Included in ρc
[2]	k=k (θ) 26-36	ρc=ρc (θ) 0.003-0.005	Included in ρc
[3]	A: 45 B: 120	--	---------------
[5]	k=k (θ) 40 -70	ρc=ρc (θ) 0.002-0.005	Algorithm
[6]	idem [5]	idem [5]	Included in ρc
[10]	k=k (θ) 32-66	ρc=ρc (θ) 0.003-0.006	---------------
[11]	k=k (θ) 28-60	ρc=ρc (θ) 0.004-0.007	---------------
[12]	k=k (θ) 48-65	ρc=ρc (θ) 0.004-0.007	---------------
Adopted	60	0.006	---------------

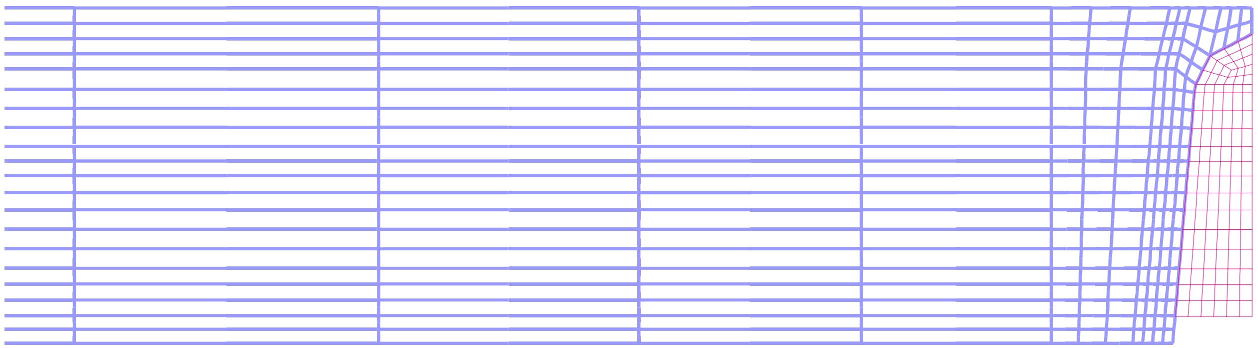
References in:

T.Pérez, R.A.Radovitzky and E.N.Dvorkin, "On a thermal model for SAW multipass butt welds", Proceedings Third Int. Conf. on Trends in Welding Research, Gatlinburg, Tennessee, June 1992, (Ed. S.A.David and J.M.Vitek), ASM International, 1993.

Linepipes welding

The numerical model includes :

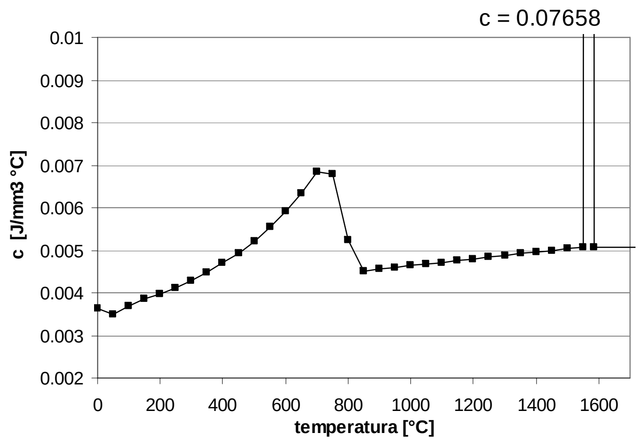
- Convection and radiation heat transfer.
- Temperature dependent material (specific heat and conductivity). Latent heat due to phase change.
- Heat input as a function of the voltage, current intensity and wire feed speed during each pass.
- Birth of elements that model the welding material.



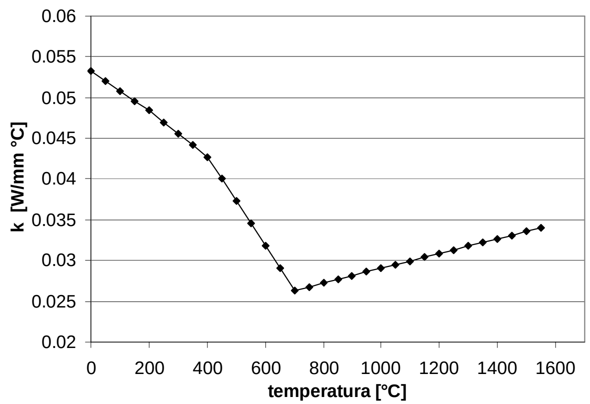
Linepipes welding

Properties in function of the chemical composition and temperature

C = 0.110	Mn = 1.020	Si = 0.250	P = 0.012	S = 0.002
Mo = 0.080	Cr = 0.080	V = 0.044	Nb= 0.022	Ni = 0.090
Cu = 0.120	Sn = 0.006	Al = 0.026	Ti = 0.010	



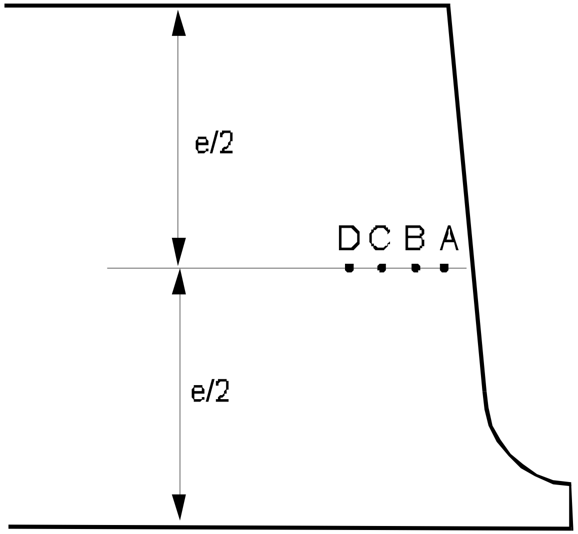
Calorific capacity



Thermal conductivity

Linepipes welding

CRC-Evans Automatic Welding test



Distance of the surface

A = 0.5 mm

B = 1 mm

C = 1.5 mm

D = 2 mmd

Linepipes welding

Heat input

$$Q_T = \eta V I$$

Q_T : effective power transferred by the arc [Watt]
η : arc efficiency (0.9)
V : voltage [Volt]
I : current [Ampere]

The total heat input is supposed to be decomposed in surface flux and in energy carried by the molten filler metal.

$$Q_T = Q_S + Q_L$$

$$Q_L = \left[\int_{\theta_o}^{\theta_a} \rho c \, d\vartheta + \sum_i \rho L_i \right] V_m$$

Q_S: surface heat flux [Watt]
Q_L: heat stored in the filler metal [Watt]
θ_o: room temperature [C]
θ_a: adopted molten filler metal temperature [1530 C]
ρc: specific heat per unit volume [J/mm^{3}C]
L_i: Latent heat per unit mass [J/grC]
V_m: filler metal deposition rate [mm^3/sec]

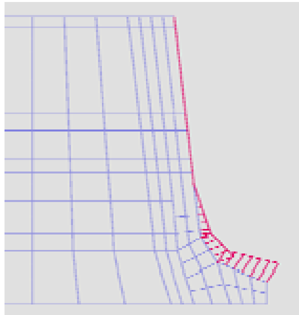
Linepipes welding

$$q(t) = \frac{3Q_{\mathrm{Arc}}}{\pi r_{\mathrm{a}}^{2}} \exp\left[-\left(\frac{r(t)}{r_{\mathrm{a}}}\right)^{2}\right]$$

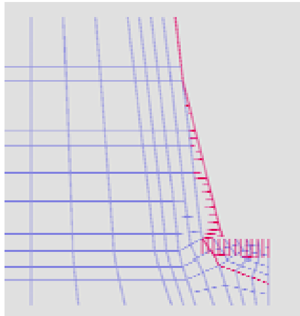
$$Q_{\mathrm{Arc}} = \eta I U - Q_{\mathrm{Wire}}.$$

Linepipes welding

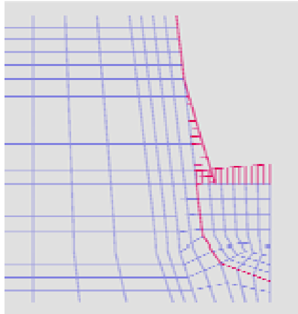
Heat input



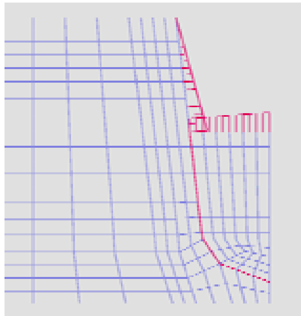
$Q_{max} = 62.05\ W/mm^2$



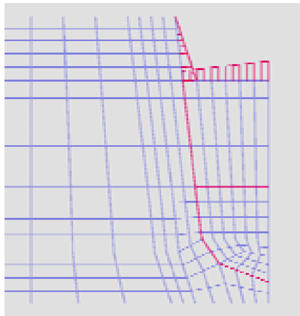
$Q_{max} = 37.89\ W/mm^2$



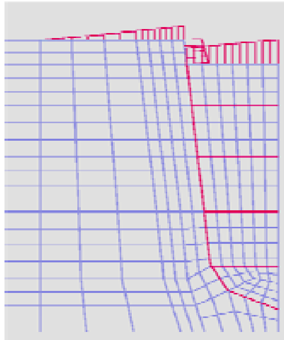
$Q_{max} = 48.80\ W/mm^2$



$Q_{max} = 44.67\ W/mm^2$



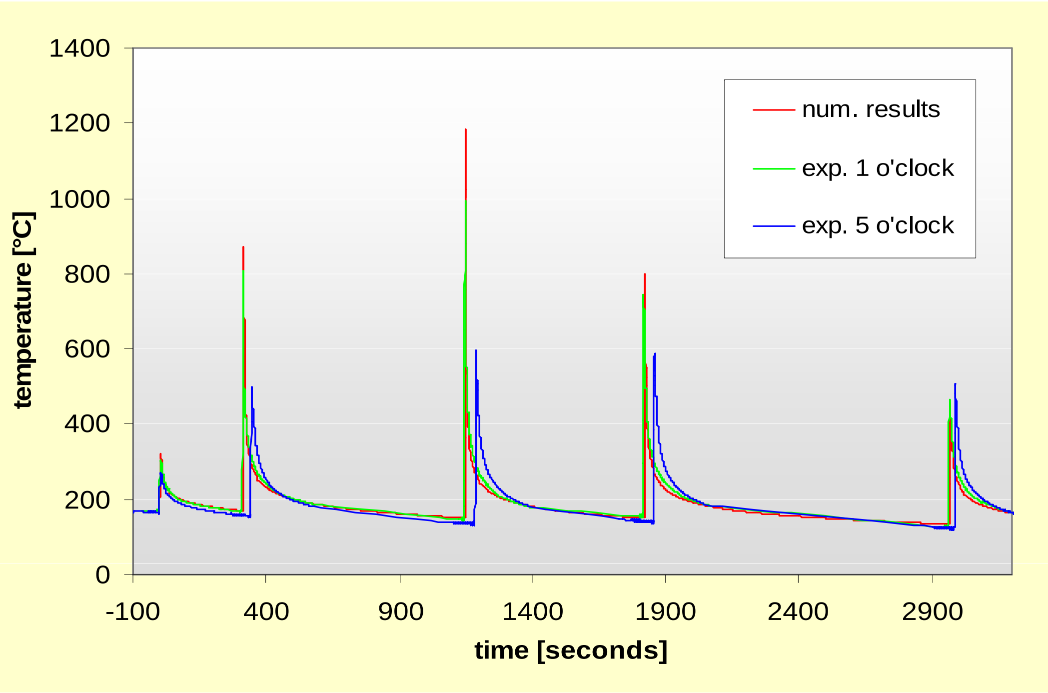
$Q_{max} = 60.31\ W/mm^2$



$Q_{max} = 33.70\ W/mm^2$

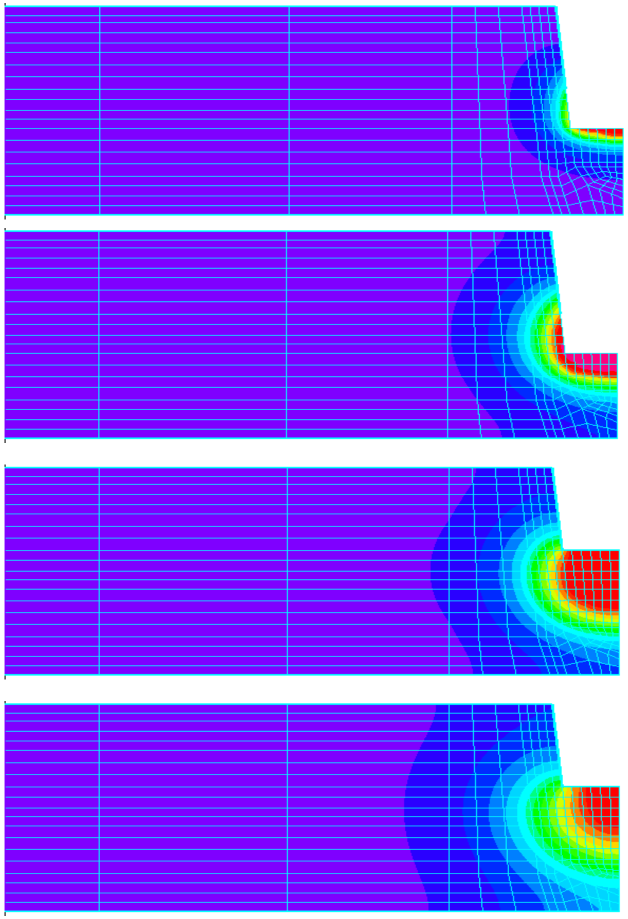
Linepipes welding

Comparison between the measured temperatures and the numerically predicted ones



Results for point B (1mm from the surface) shown on the finite element mesh

Linepipes welding

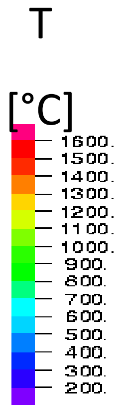


time = -0.8 s

time = -0.1 s

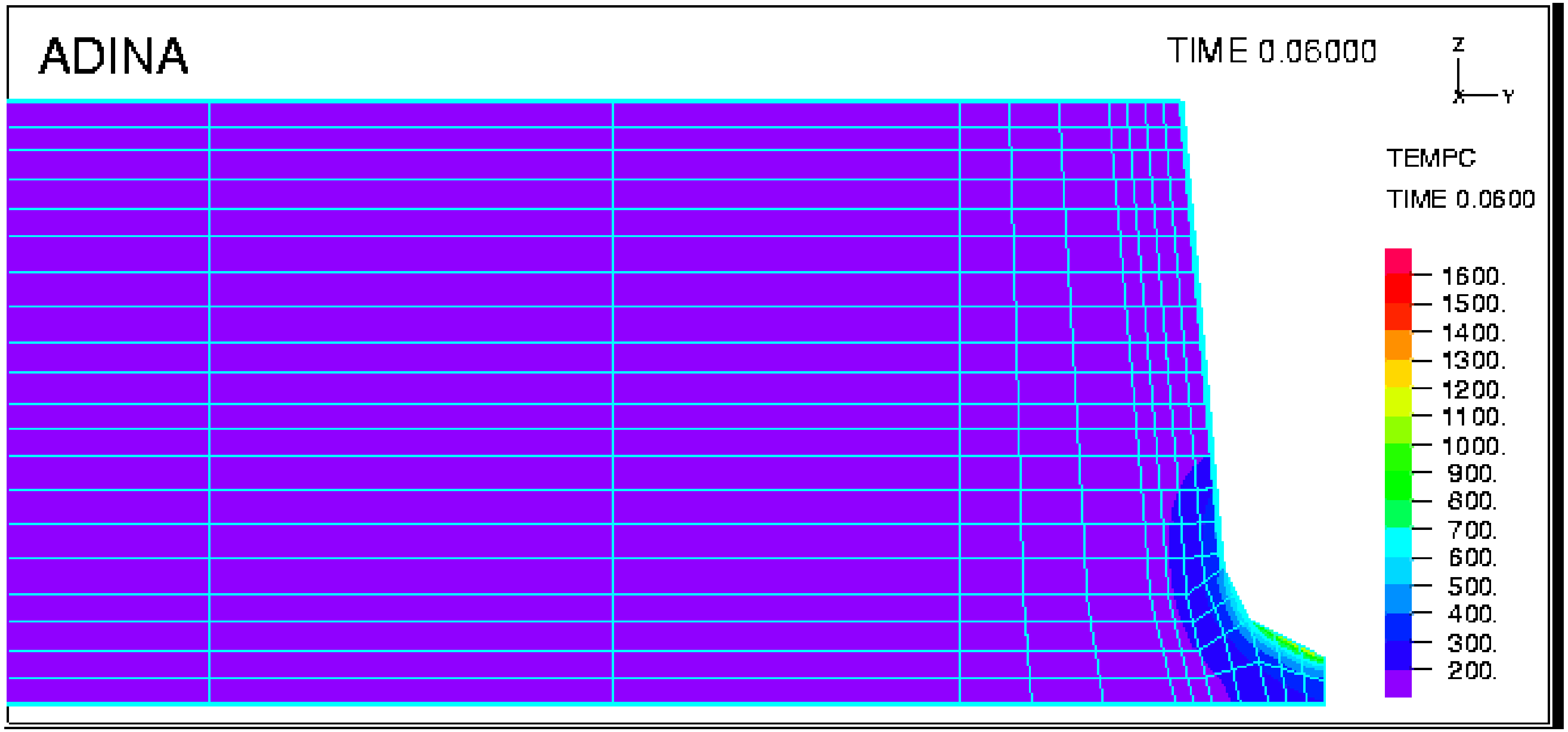
time = 0.1 s

time = 0.5 s



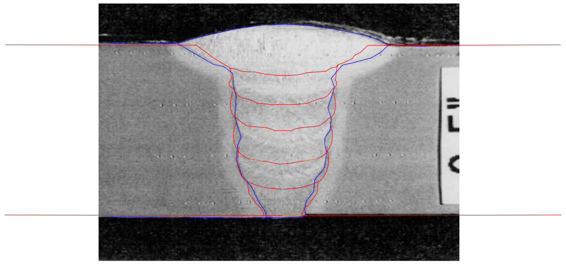
time = 0 indicates the birth of the welding material in the fill 2

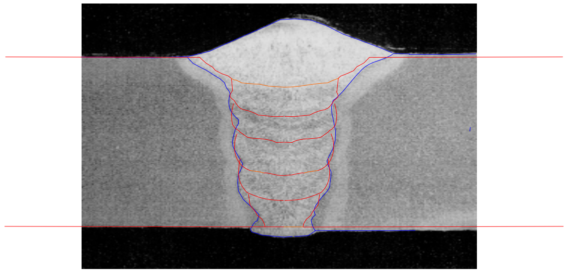
Linepipes welding



Linepipes welding

Liquid pool zone

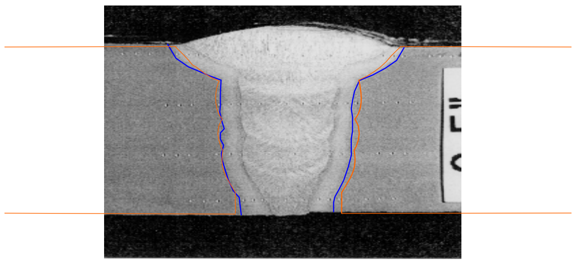


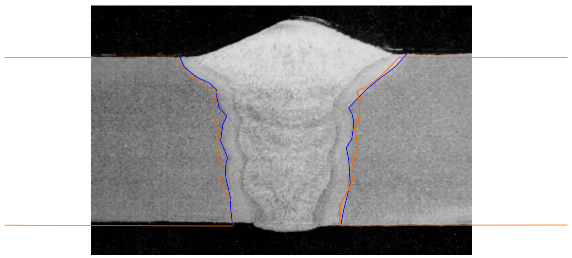


Red numerical values

Blue experimental values

Haz





$T > 850\ ^{\circ}C$

Phase transformation from phase g to phase (a + g)

Linepipes welding

Typical mechanical properties to be used as input
Typical carbon steel

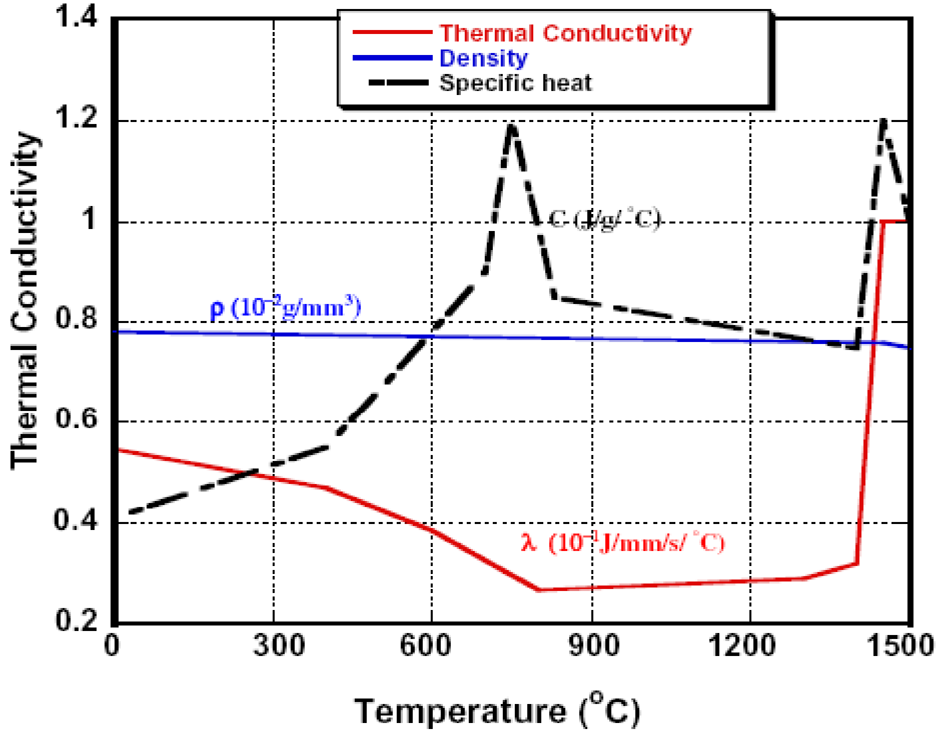


Fig. 3. Temperature-dependent thermal–physical properties.

Linepipes welding

Typical mechanical properties to be used as input

Typical carbon steel

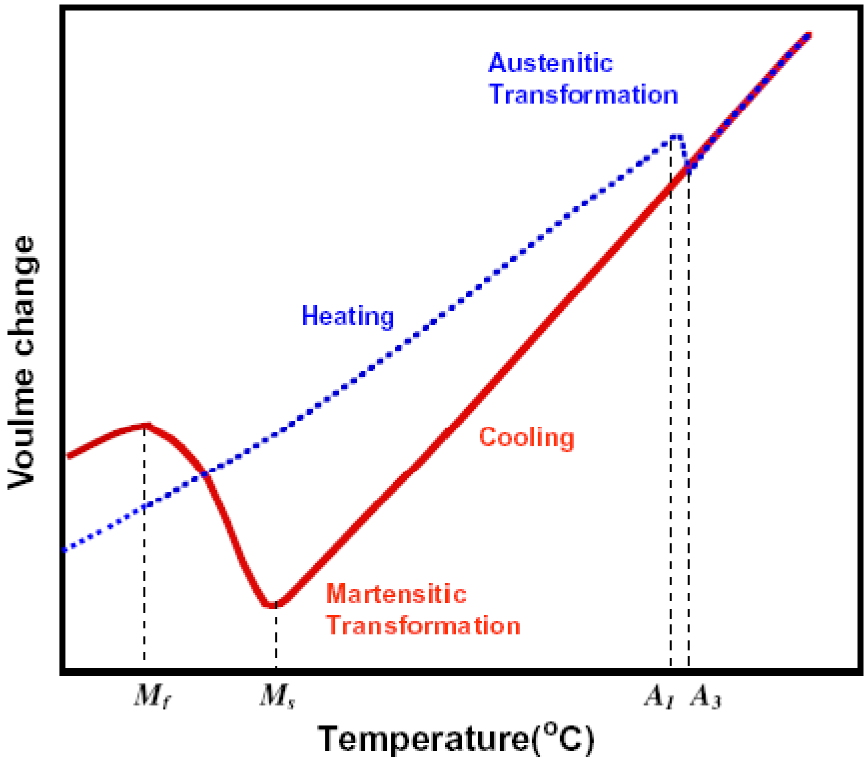


Fig. 4. Schematic diagram of volume change due to phase transformation.

Linepipes welding

Typical mechanical properties to be used as input
Typical carbon steel

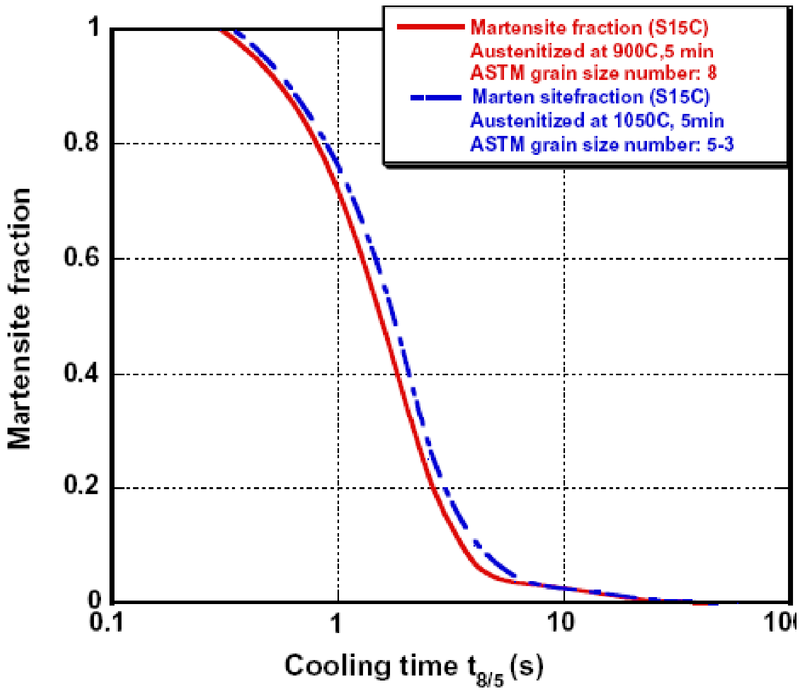


Fig. 5. Martensite fraction as a function of cooling time $t_{8/5}$ for S15C steel.

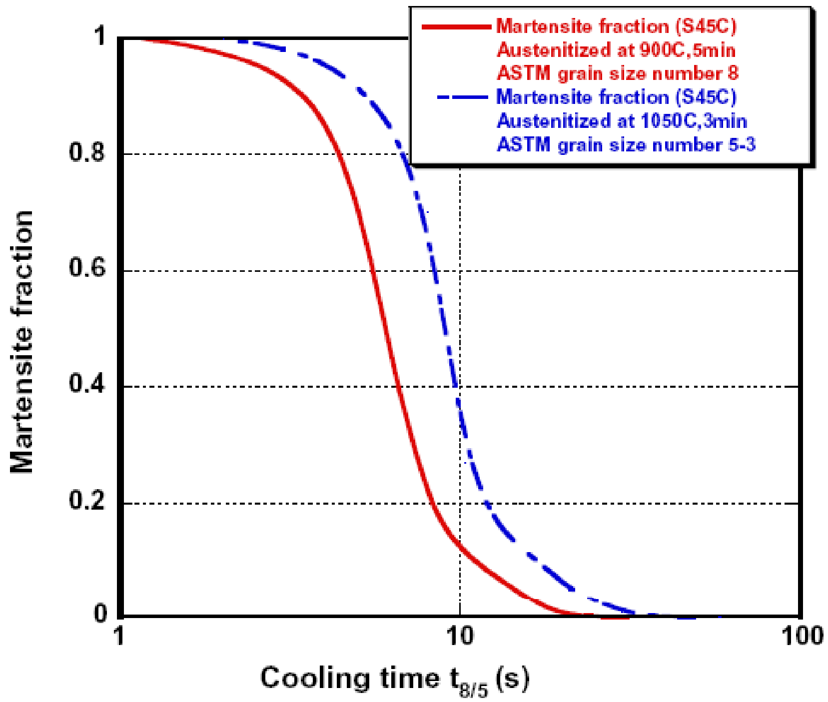


Fig. 6. Martensite fraction as a function of cooling time $t_{8/5}$ for S45C steel.

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Linepipes welding

Typical mechanical properties to be used as input
Typical carbon steel

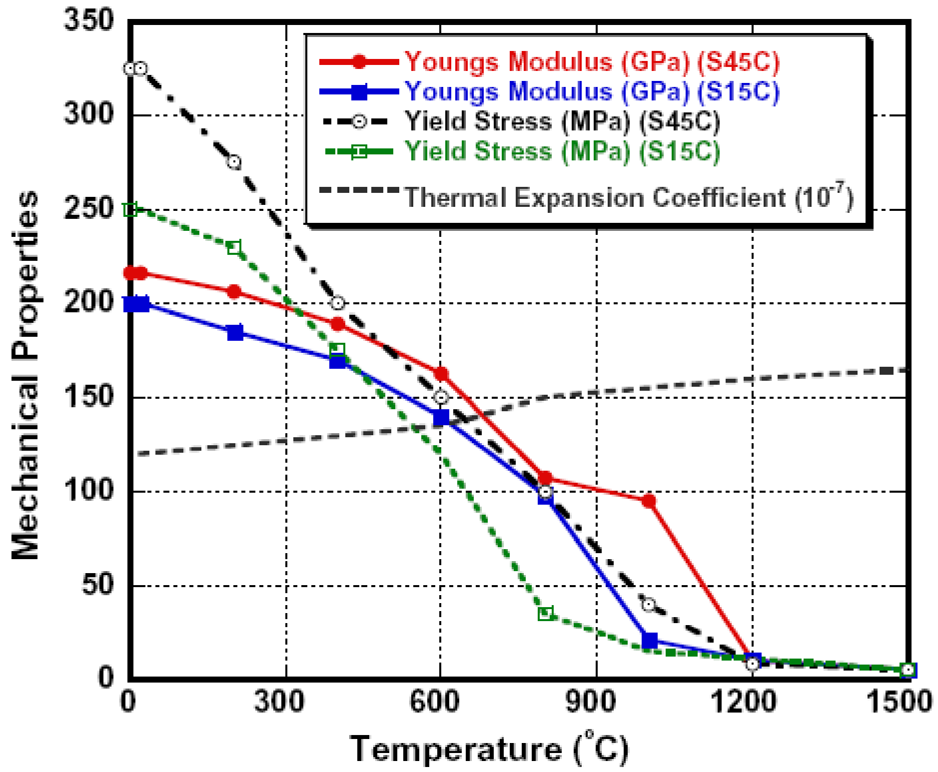

Fig. 7. Temperature-dependent mechanical–physical properties.

Linepipes welding

Typical mechanical properties to be used as input . Stainless steel

5th International Conference on Trends in Welding Research, June 1-5, 1998, Pine Mountain, GA

Finite Element Modeling and Validation of Residual Stresses in 304L Girth Welds

J. J. Dike
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Los Alamos, NM 87545

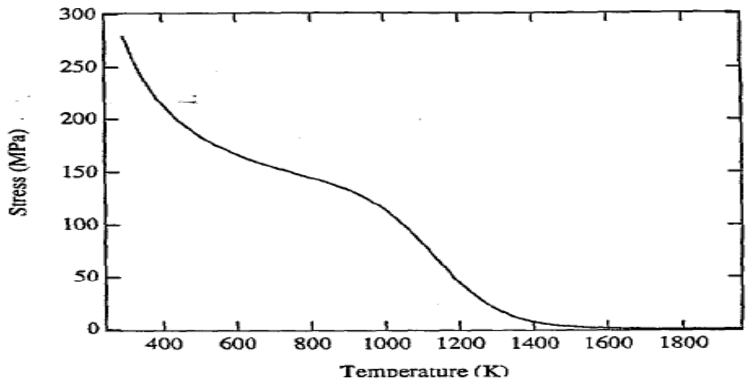

Figure 3. Yield stress of 304L stainless steel used in mechanical finite element analyses as a function of temperature.

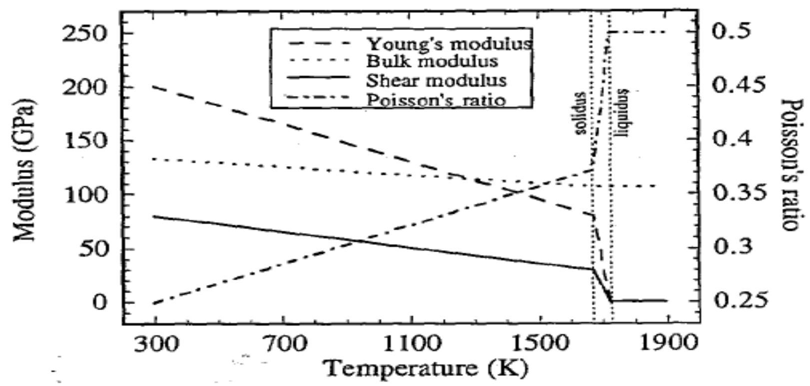

Figure 4. Elastic properties of 304L stainless steel used in mechanical finite element analyses.

Results sought in welding simulations

- Residual stresses
- Distortions

Examples from the literature

Table 5

Chemical composition, calculated transformation temperature range (ΔT_{tr}), and measured distortion (β) for two manual metal arc multi-pass weld deposits [6,16]

Composition, wt%						ΔT_{tr} (°C)	β (°)
C	Si	Mn	Ni	Mo	Cr		
0.06	0.5	0.9	–	–	–	802–400	14.5
0.06	0.3	1.6	1.7	0.4	0.35	422–350	8.0

Examples from the literature

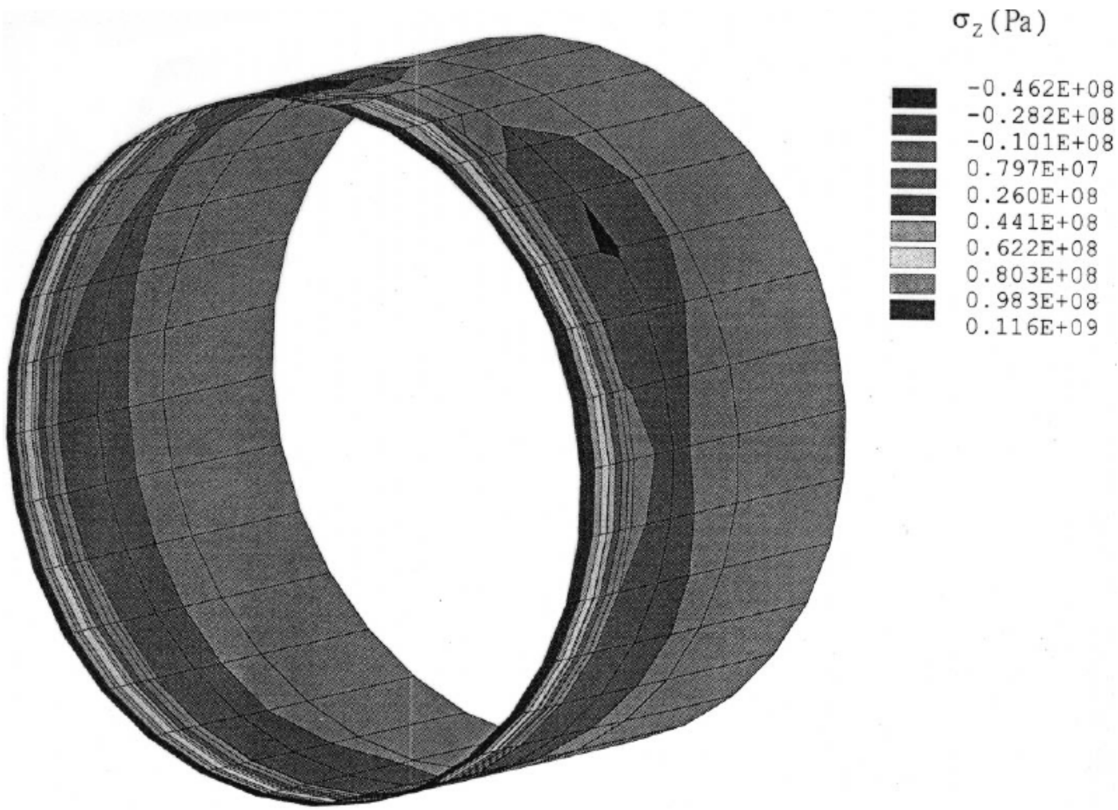

Fig. 9. Contours of residual axial stress at inner surface of 324 mm schedule 10 pipe.