Using LS-DYNA To Model Hot Stamping

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A. Shapiro, “Finite Element Modeling of Hot Stamping”, Steel research International, p. 658, Vol. 80, September 2009.

Table of Contents

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Table of Contents

Katana: how to make a Japanese sword

The sword smiths of China during the Tang Dynasty (618-907) are often credited with the forging technologies that the Japanese used in later centuries. These technologies include folding, inserted alloys, and quenching of the edge. Okazaki-san is recognized as Japan's greatest sword smith creating such weapons as the katana (14th century).

Heat the steel to the color of the moon in February

Transfer the blank to the anvil

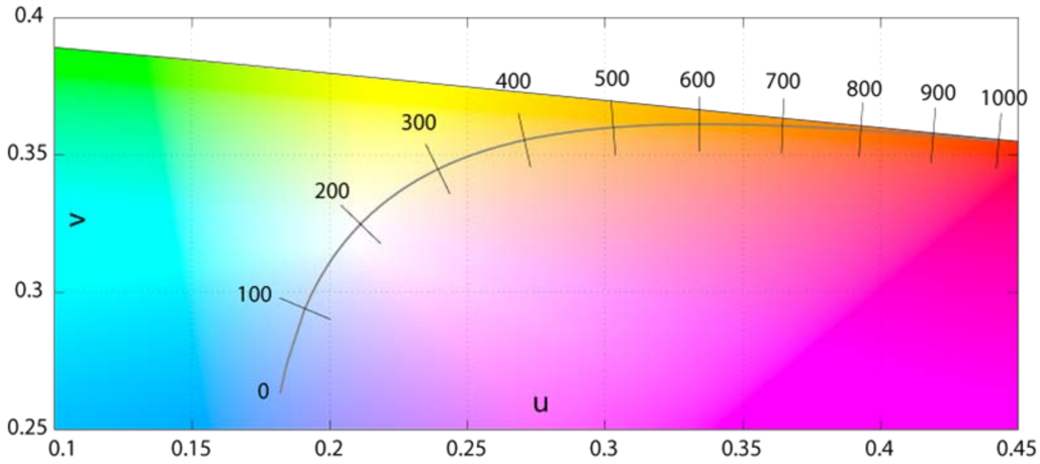
Form the blank with a hammer and lots of muscle

Quench the blade.

Katana: how to make a Japanese sword

Temperature of the Moon in February

A color triangle is an arrangement of colors within a triangle, based on the additive combination of 3 primary colors (RGB) at its corners. The correlated color temperature is the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus. Shown is the Plankian locus (in mired) overlaid on the color triangle.



NASA 2/23/09

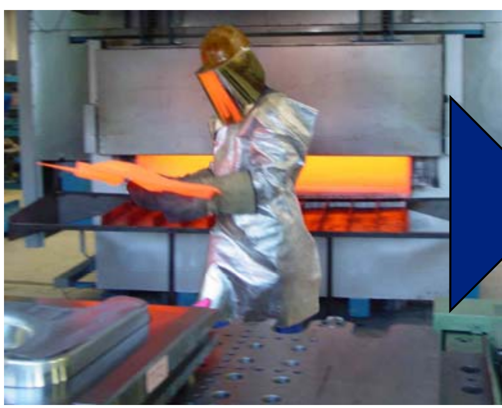
$$T_{moon} = \frac{1*10^6}{M} \approx \frac{1*10^6}{900} = 1111\ K = 838\ C$$

http://en.wikipedia.org/wiki/Color_temperature

B-pillar: how to make Car parts

Courtesy of Mercedes Car Group, Sindelfingen , Germany

1. Heat



2. Transfer

3. Form

4. Quench

Numisheet 2008 Benchmark BM03

proposed by Audi

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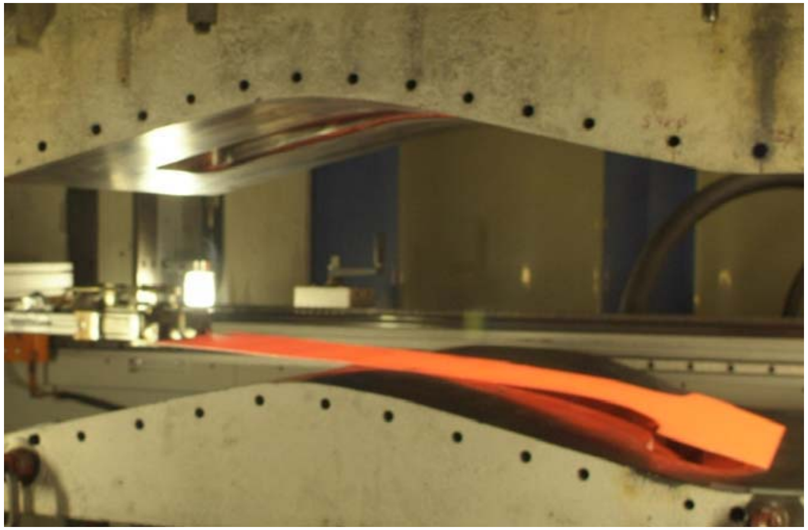

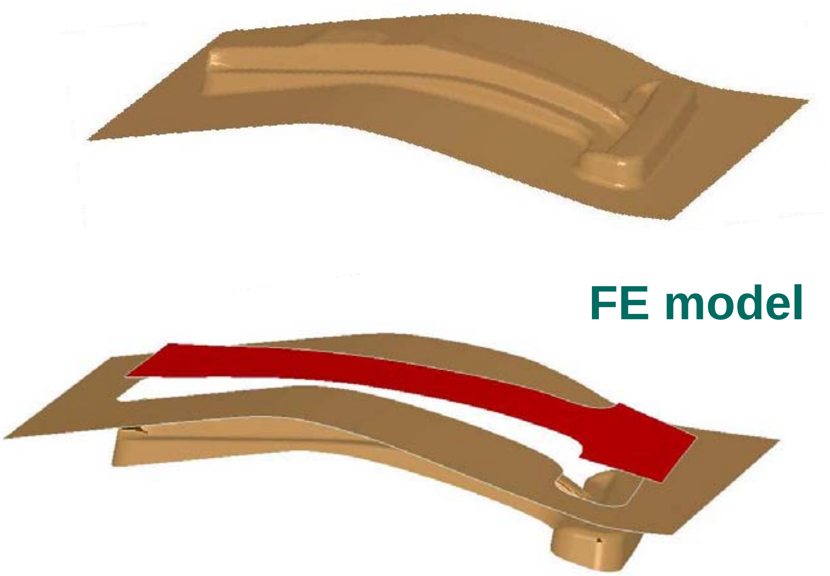

FE model

Benchmark process specification

1. Heating of the blank to 940C.
2. Transport from the oven into the tool 6.5 sec.
3. Temperature of the blank at the beginning of the die movement 810C.
4. Forming process time 1.6 sec.
5. Quench hold time in the tool 20 sec.
6. Cool down to room temperature 25C

Symbols and values

metal

Blank	
material	**22MnB5**
dimensions	
***l*, thickness**	**0.00195 m**
length	**1m**
width	**0.25 m**
properties	
ρ, density kg/m^3	**7830.**
Cp, heat capacity J/kgK	**650.**
k, thermal conductivity W/mK	**32.**
λ, latent heat, kJ/kg	**58.5**
α, linear expansion, 1/C	**1.3e-05**
E, Young’s modulus, Gpa	**100.**
μ, Poisson’s ratio	**0.30**

Symbols and values

air at 483C

$$T_{film} = \frac{940+25}{2} = 483.$$

Air properties at 483 C	
ρ, density, kg/m^3	0.471
Cp, heat capacity, J/kg C	1087.
k, thermal conductivity, W/m C	0.055
μ, viscosity, kg/m s	3.48e-05
β, volumetric expansion, 1/C	1.32e-03

Newtonian heating or cooling

convection lumped parameter model

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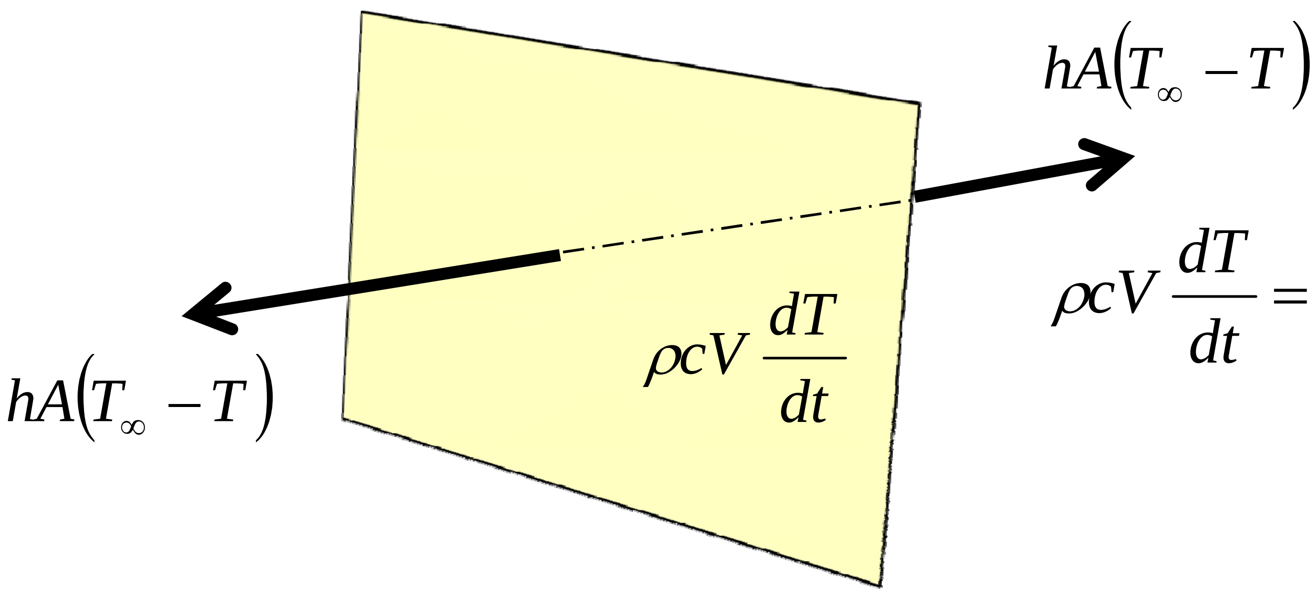
Consider an object being heated from some uniform initial temperature, T_i. If the object is of high thermal conductivity, then its internal resistance can be ignored, and we can regard the heat transfer process as being controlled solely by surface convection.



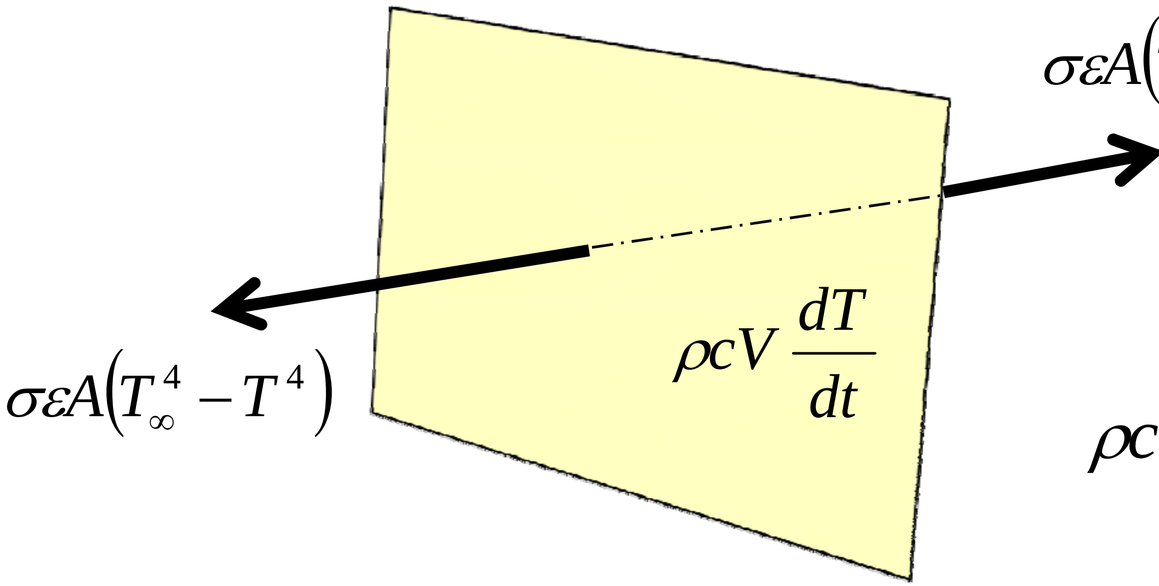
$$\rho c V \frac{dT}{dt} = 2hA(T_\infty - T)$$

The solution is

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\left(\frac{2hA}{\rho c V}\right)t}$$

Newtonian heating or cooling

radiation lumped parameter model



$$\rho c V \frac{dT}{dt} = 2\sigma\varepsilon A\left(T_\infty^4 - T^4\right)$$

The solution to this differential equation between the limits (*$T=T_i$* @ t=0) and (*$T=T_f$* at t), is

$$t = \frac{\rho c V}{2A\sigma\varepsilon}\left[\frac{1}{4T_\infty^3}\ln\frac{\left(T_f + T_\infty\right)/\left(T_f - T_\infty\right)}{\left(T_i + T_\infty\right)/\left(T_i - T_\infty\right)} + \frac{1}{2T_\infty^3}\left(\tan^{-1}\frac{T_f}{T_\infty} - \tan^{-1}\frac{T_i}{T_\infty}\right)\right]$$

Blank heating and transport into tools

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Our starting point for the FE analysis was Process Step Specification 3. However, we performed a hand calculation to verify steps 1 and 2.

The following analytical equation can be used to calculate the time for the blank to cool by radiation from T_i=940C to T_f=810C during the transport operation from the oven into the tool. The surroundings are at T_∞=25C.

$$time = \frac{\rho C_p l}{2\sigma\varepsilon}\left[\frac{1}{4T_\infty^3}\ln\frac{(T_f + T_\infty)/(T_f - T_\infty)}{(T_i + T_\infty)/(T_i - T_\infty)} + \frac{1}{2T_\infty^3}\left(\tan^{-1}\frac{T_f}{T_\infty} - \tan^{-1}\frac{T_i}{T_\infty}\right)\right]$$

$$time = 6.68$$

The calculated time is in agreement with the benchmark specification of 6.5 sec.

σ = 5.67e-08 W/m2 K4	**ε = 1.**
ρ = 7870 kg/m3	**C_p = 650 J/kg C**
l = 1.95 mm	

Use degrees Kelvin in above equation

Blank heating and transport into tools

Blank T=810C at beginning of die movement

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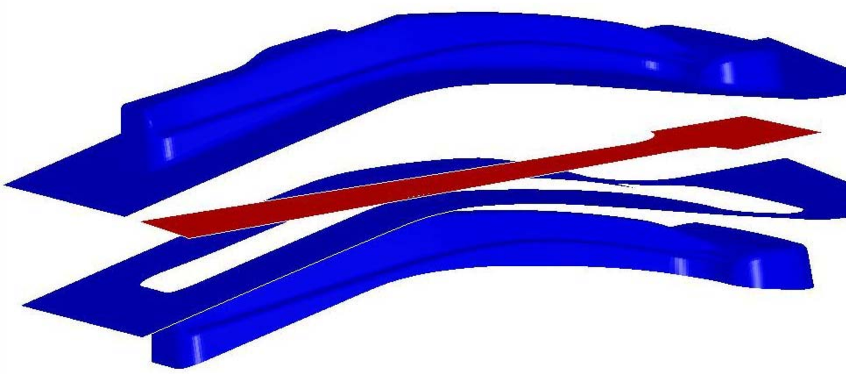
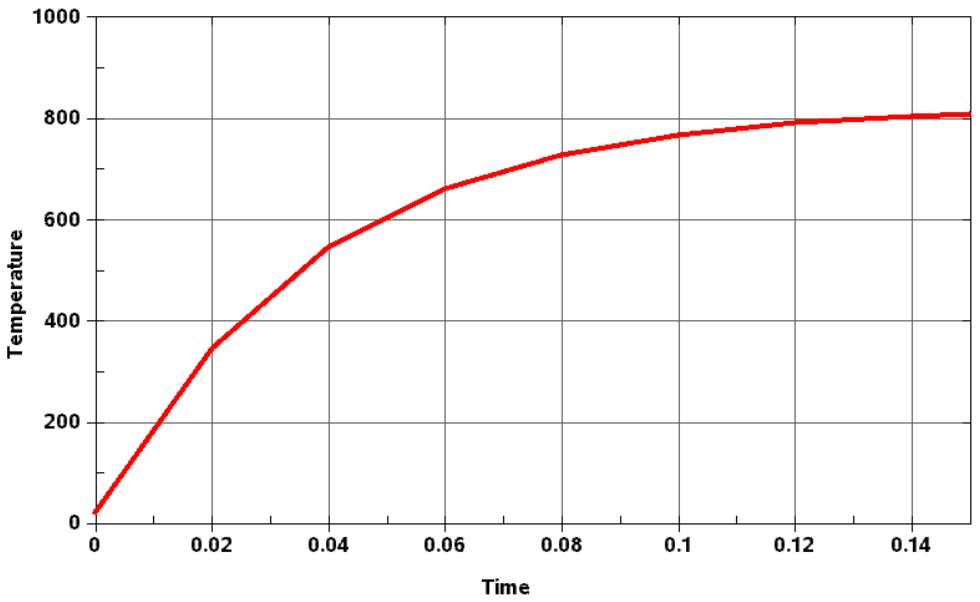
The easiest modeling technique is to define the initial temperature of the blank to be 810C. However, doing this will not calculate the thermal expansion of the blank between 25C and 810C. Therefore, the blank is heated in the FE model resulting in a thickness increase from1.95mm to 1.97mm.

The time to heat the blank is not a critical parameter for this analysis. All we want is the blank to be at 810C and have the correct thickness at the beginning of the die movement.





Blank heating and transport into tools

How do you chose an h for heating the blank

It takes 0.4 sec for the upper tool to touch the blank according to the specified tool displacement curve. Therefore, select 0.15 seconds for heating.

$$h = -\frac{\rho C_p l}{t} \ln\left(\frac{T - T_\infty}{T_i - T_\infty}\right) = -\frac{(7830)(486)(0.00195)}{(0.15)} \ln\left(\frac{809.9 - 810}{25 - 810}\right) = 444{,}000 \quad \frac{W}{m^2 C}$$

h=444,000 is a ridiculously high number and is not physically possible. But, remember that the time to heat the blank is not a critical parameter for this analysis. All we want is the blank to be at 810C and have the correct thickness at the beginning of the die movement.

Radiation & convection heat loss during transfer and forming

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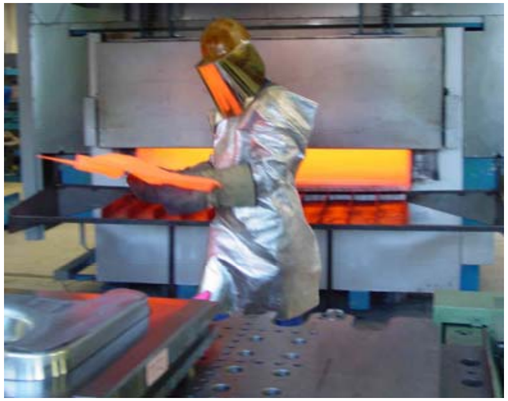
After heating the blank, it is transferred to the tools. The blank cools by convection and radiation to the environment.

1. Heat



2. Transfer

The heat loss is calculated by: $\dot{q}'' = \boldsymbol{h_{eff}} \, A \, (T_s - T_\infty)$

How do you determine $h_{eff} = h_{conv} + h_{rad}$

Radiation & convection heat loss

How to calculate coefficients

Convection

$$T_{film} = \frac{T_{surf} + T\infty}{2} = \frac{940 + 25}{2} = 483 \ C$$

$$L = \frac{2(length * width)}{lenght + width} = \frac{2(1*0.25)}{1+0.25} 0.4 \ m$$

$$Gr = \frac{g\beta\rho^2 L^3 (T_{surf} - T_\infty)}{\mu^2} = \frac{(9.8)(1.32*10^{-3})(0.471)^2(.4)^3(940-25)}{(3.48*10^{-5})^2} = 1.39*10^8$$

$$\Pr = \frac{C_p \mu}{k} = \frac{(1087)(3.48*10^{-5})}{0.055} = 0.687$$

$$h_{conv} = 0.14 \frac{k}{L}(Gr * \Pr)^{0.33} = .14 \frac{0.055}{.4}(1.39*10^8 * 0.687)^{0.33} = 8.3 \ \frac{W}{m^2 C}$$

940C + 273C = 1213K

Radiation

$$h_{rad} = \frac{\sigma\varepsilon(T_{surf}^4 - T_\infty^4)}{(T_{surf} - T\infty)} = \frac{(5.67*10^{-8})(0.8)(1213^4 - 298 \ )}{(1213 - 298)} = 107 \ \frac{W}{m^2 K}$$

Radiation & convection heat transfer coefficients

$h_{conv} + h_{rad} = h_{eff}$

T [C]	h_{conv}	h_{rad}	h_{eff} [W/m^{2}C]
50	5.68	5.31	11.0
100	6.80	6.8	13.6
200	7.80	10.8	18.6
300	8.23	16.3	24.5
400	8.43	23.6	32.0
500	8.51	33.0	41.5
600	8.52	44.8	53.3
700	8.50	59.3	67.8
800	8.46	76.6	85.1
900	8.39	97.2	106.
1000	8.32	121.	129.

Note:

a) h_{rad} dominates

b) h_{conv} @ T>400 uncertain

Temperature of the blank at tool contact

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After the blank is positioned within the tools, it continues to lose heat by convection and radiation to the environment. The benchmark specifies a heat transfer coefficient of h_{air}=160 W/m^{2}K. We feel that this value is too high and h_{air}=115 is more appropriate. However, a hand calculation reveals that the blank only drops by 10C before the tools make contact. Therefore, knowing h_{air} precisely is not important. We ignored modeling this energy loss (i.e., temperature and thickness change) in our FE model.

$$T = T_\infty + (T_i - T_\infty)e^{-\left(\frac{2ht}{\rho C_p l}\right)}$$

t = time until top tool contacts blank

$$800 = 25 + (810 - 25)e^{-\left(\frac{2(160)(0.4)}{(7870)(650)(0.00195)}\right)}$$

Heat transfer to air and to dies

Top blank surface

Convection + radiation heat loss to the environment, use:

***BOUNDARY_CONVECTION**

***BOUNDARY_RADIATION**

Bottom blank surface

Turn off thermal boundary conditions when parts are in contact.

***CONTACT_(option)_THERMAL**

parameter BC_FLAG = 1

There will be a through thickness temperature gradient in the blank caused by the different heat loss rates from the surfaces.

***CONTROL_SHELL**

ISTUPD = 1 → calculate shell thickness change

TSHELL= 1 → 12 node thick thermal shell, T gradient through thickness

Heat transfer to air and to dies

The **top surface** loses heat to the environment by convection and radiation.

The **bottom surface** loses heat to the tool. The contact heat transfer to the tool is **10x** greater than conv. + rad. loss.

What is h contact ?

There will be a through thickness temperature gradient in the blank due to the large difference in heat loss rates from the top and bottom surfaces. This is calculated using the 12 node thick thermal shell formulation developed by G. Bergman & M. Oldenburg at Lulea University.

Contact parameters

(1) Friction function of T (2) heat transfer function of P

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```
*CONTACT_(option)_THERMAL_FRICTION
lcfst  lcfdt  formula  a  b  c  d  lch
```

Mechanical friction coefficients vs. temperature

Static → $\mu_s = \mu_s * lcfst(T)$

Dynamic→ $\mu_d = \mu_d * lcfdt(T)$

1	h(P) is defined by load curve “a”	such as GE data
2	h(P) = a + bP + cP2 + dP3	polynomial curve fit
3	$h(P)=\frac{\pi k_{gas}}{4\lambda}\left[1.+85\left(\frac{P}{\sigma}\right)^{0.8}\right]=\frac{a}{b}\left[1.+85\left(\frac{P}{c}\right)^{0.8}\right]$	I.T. Shvets, “Contact Heat Transfer between Plane Metal Surfaces”, Int. Chem. Eng., Vol4, No. 4, p621, 1964.
4	$h(P)=a\left[1-\exp\left(-b\frac{P}{c}\right)\right]^{d}$	Li & Sellers, Proc. Of 2nd Int. Conf. Modeling of Metals Rolling Processes, The Institute of Materials, London, 1996.

Contact parameters

In-line FORTRAN function

LCH	**= 0**	**not defined**
	< 0	**h(temperature)**
	> 0	**h(time)**
	> nlcur	**function(time, Tavg, Tslv, Tmsr, pres, gap)**

```
*DEFINE_FUNCTION
101
h101(pres)=25.+25.e-07*pres+25.e-14*pres**2+25.e-21*pres**3
```

Contact parameters

In-line FORTRAN function with load curve


```
*DEFINE_FUNCTION_TABULATED
$#       fid      definition
         100      acoef(tavg)
$# title
acoef
$#                tavg                  acoef
                    0.                    25.
                 1000.                    25.
*DEFINE_FUNCTION
101
h101(pres,tavg)=acoef(tavg)+25.e-07*pres+25.e-14*pres**2
+25.e-21*pres**3
```

Contact parameters

Function specified by C program


```
*DEFINE_FUNCTION
$#     fid     defintion
       101     h a function of pressure
float contact(float tslv, float tmsr, float pres)
{
 float tmean, acoef, h ;
 tmean=(tslv+tmsr)/2. ;
 acoef=.125*tmean ;
 h=acoef+25.e-07*pres+25.e-14*pres**2+25.e-21*pres**3 ;
 printf ("tmean= %f   acoef= %f   h= %f \n",tmean,acoef,h);
 return (h) ;
}
```

Contact parameters

Contact conductance function of pressure

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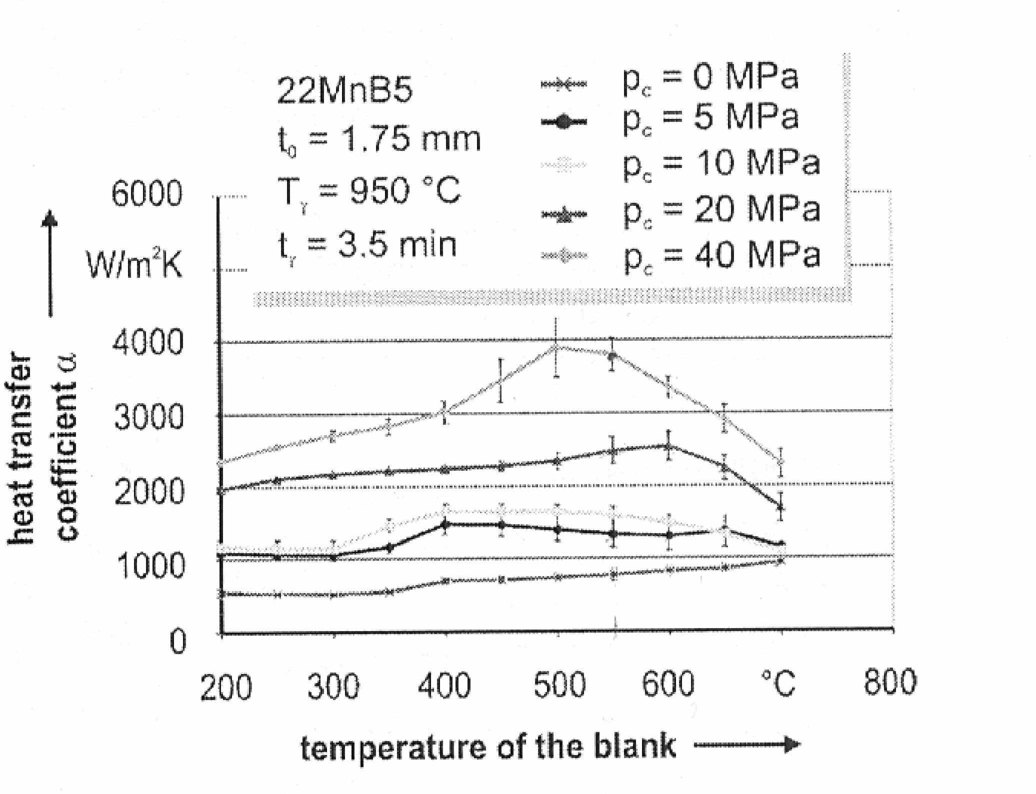
M. Merklein and J. Lechler, "Determination of Material and process Characteristics for Hot Stamping Processes of Quenchable Ultra High Strength Steels with Respect to a FE_based Process design", SAE Technical Paper 2008-01-0853, April, 2008.



Numisheet BM03 data

P [MPa]	h [W/m²K]
0	1300
20	4000
35	4500

Contact parameters

How do you calculate h(P) at the interface

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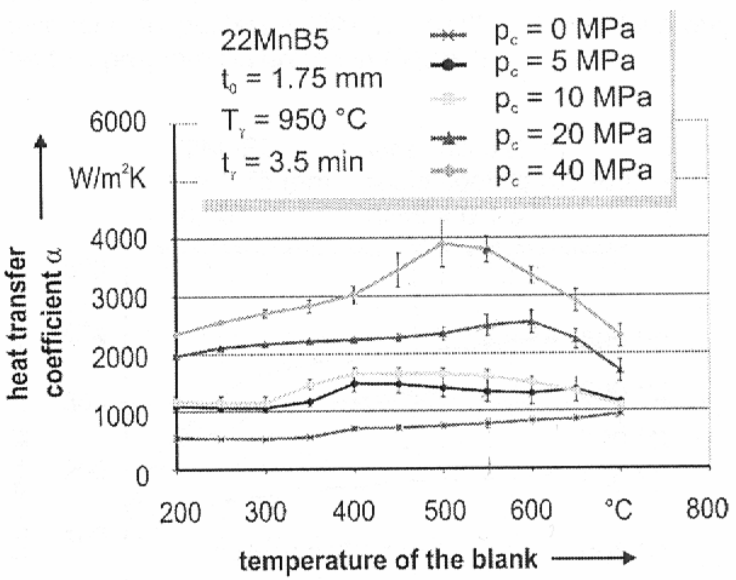

P	h @ 550C (curve)	h calculated
0	750	750
5	1330	1330
10	1750	1770
20	2500	2520
40	3830	3830

$$h = \frac{k\pi}{4\lambda}\left[1 + 85\left(\frac{P}{\sigma_r}\right)^{0.8}\right]$$

h = contact conductance [W/m²C]
k = air thermal conductivity
0.059 W/mC at 550 C
λ = surface roughness [m]
P = interface pressure [MPa]
σ_r = rupture stress [MPa]

M. Merklein and J. Lechler, "Determination of Material and process Characteristics for Hot Stamping Processes of Quenchable Ultra High Strength Steels with Respect to a FE_based Process design", SAE Technical Paper 2008-01-0853, April, 2008.

I.T. Shvets, "Contact Heat Transfer Between Plane Metal Surfaces", Int. Chem. Eng, Vol 4, No 4, p621, 1964.

Contact parameters

How do you calculate h(P) at the interface

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1. Using curve data, solve the equation for λ at (P, h) = (0, 750).

$$750 = \frac{(0.059)\pi}{4\lambda}\left[1 + 85\left(\frac{0}{\sigma_r}\right)^{0.8}\right]$$

λ = 61.8e-05

2. Using curve data and the above value for λ, solve the equation for σ_r at (P, h) = (40, 3830).

$$3830 = \frac{(0.059)\pi}{4(6.18 * 10^{-5})}\left[1 + 85\left(\frac{40}{\sigma_r}\right)^{0.8}\right]$$

σ_r = 1765

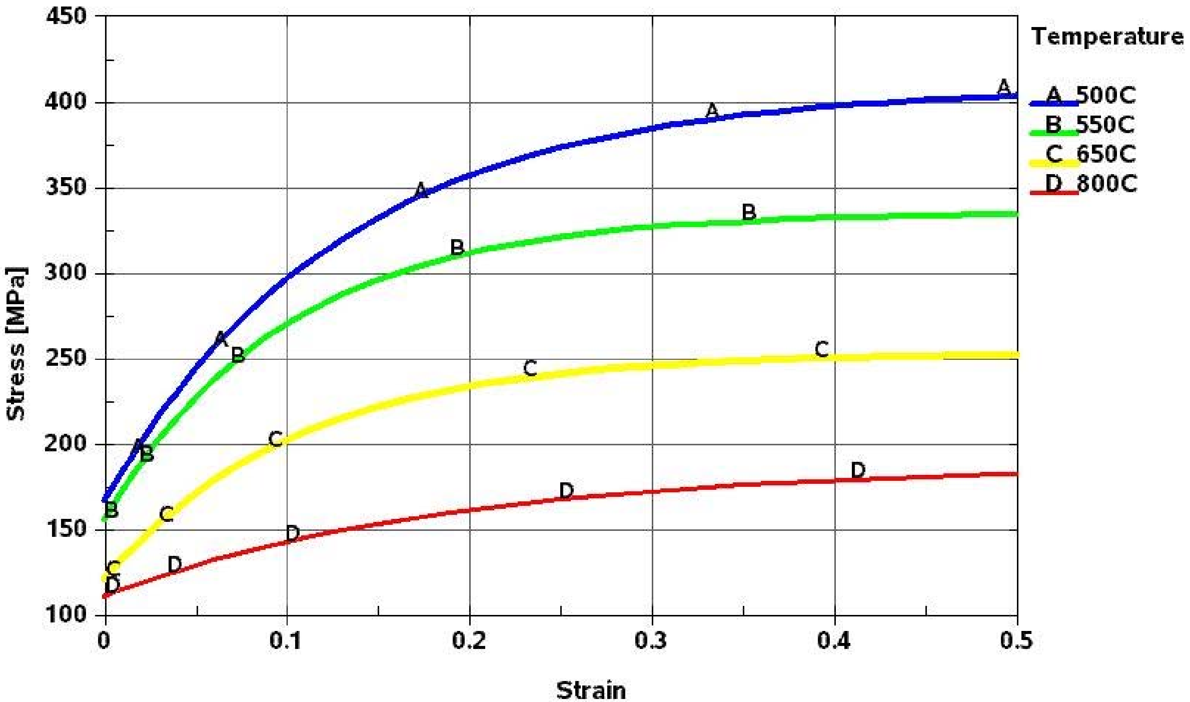
3. Now use the equation to calculate h(P)

$$h = \frac{(0.059)\pi}{4(6.18 * 10^{-5})}\left[1 + 85\left(\frac{p}{1765}\right)^{0.8}\right]$$

Numisheet 2008 data for 22MnB5

de/dt [s^{-1}]	T [°C]				
	500	550	650	700	800
0.01					
0.1					
1.0					

A material model (MAT_106) was used that allowed interpolation of the σ vs. ε data as a function of temperature at a specified strain rate.



MAT_106 : Elastic Viscoplastic Thermal

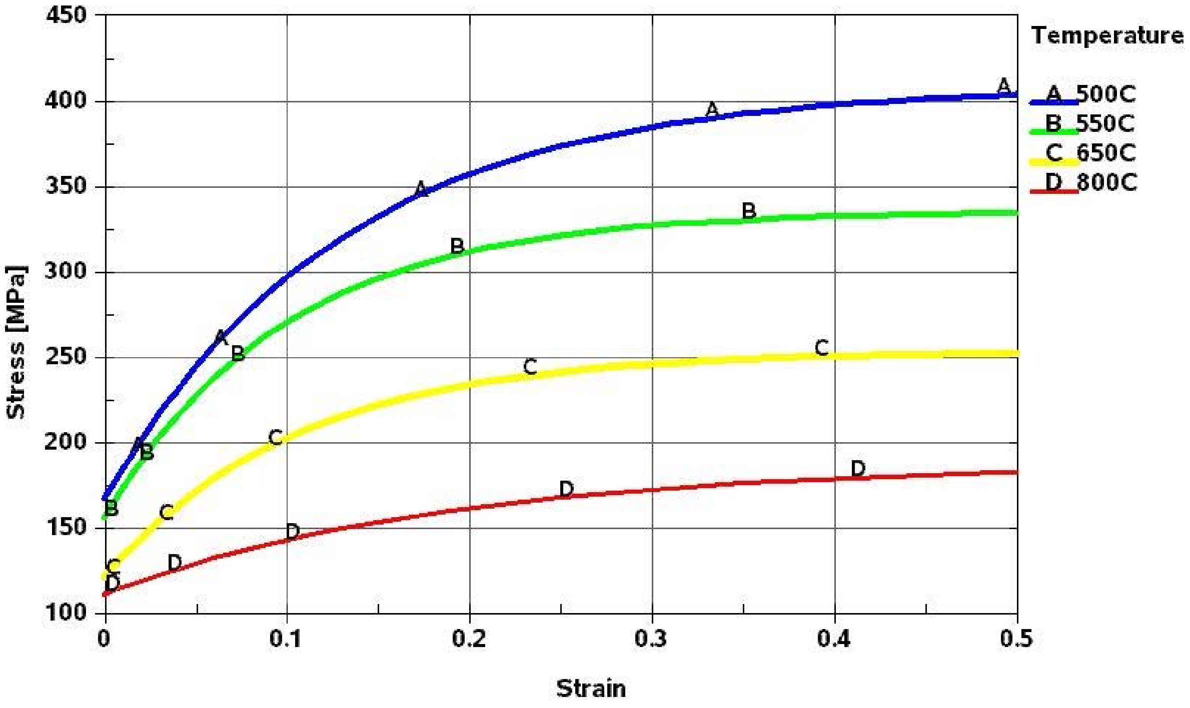
1	2	3	4	5	6	7	8
MID	RO	E	PR	SIGY	ALPHA	LCSS	
C	P	LCE	LCPR	LCSIGY			LCALPH
LCC	LCP						

MAT_106 : Elastic Viscoplastic Thermal

How to enter σ vs. ε vs. T

***DEFINE_TABLE**
500
550
650
800
***DEFINE_CURVE**
(stress,strain) at T=500
.
***DEFINE_CURVE**
(stress,strain) at T=550
.
***DEFINE_CURVE**
(stress,strain) at T=650
.
***DEFINE_CURVE**
(stress,strain) at T=800
.

Material: 22MnB5 ($d\varepsilon/dt=0.1\ s^{-1}$)
Data from University of Erlangen



MAT_106 : Elastic Viscoplastic Thermal

Cowper and Symonds model

LSTC

Viscous effects are accounted for using the Cowper and Symonds model, which scales the yield stress with the factor

$$1+\left(\frac{\dot{\varepsilon}_{eff}^{P}}{C}\right)^{1/P}$$

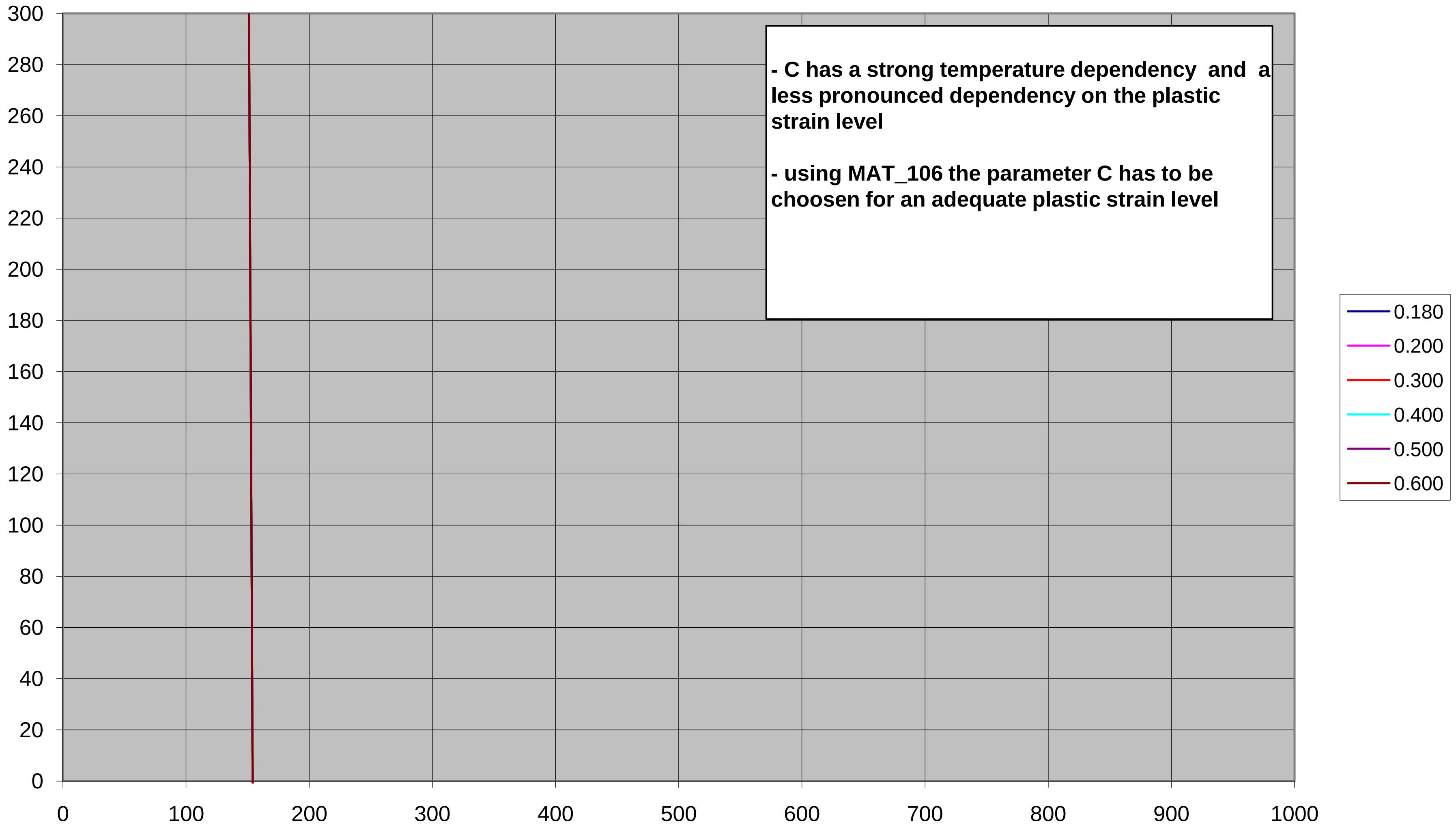
Temp [C]	20	100	200	300	400	500	600	700	800	900	1000
E [MPa]	212	207	199	193	166	158	150	142	134	126	118
v	0.284	0.286	0.289	0.293	0.298	0.303	0.310	0.317	0.325	0.334	0.343
p	4.28	4.21	4.10	3.97	3.83	3.69	3.53	3.37	3.21	3.04	2.87
c	6.2e9	8.4e5	1.5e4	1.4e3	258.	78.4	35.4	23.3	22.2	30.3	55.2

Courtesy of David Lorenz, Dynamore, Stuttgart, Germany.

MAT_106 : Elastic Viscoplastic Thermal

Parameter C vs. T at different plastic strains

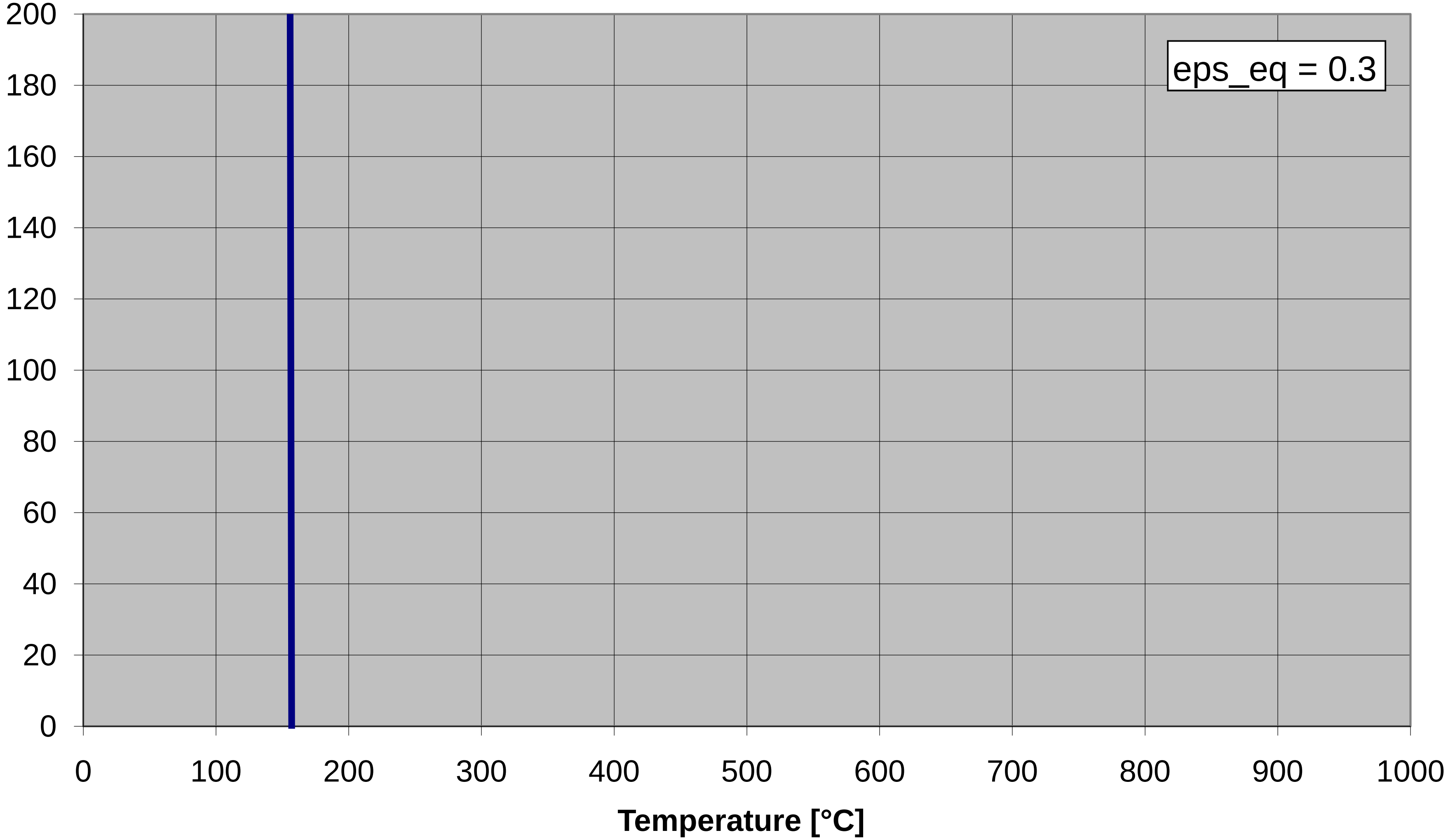
LSTC



MAT_106 : Elastic Viscoplastic Thermal

Parameter C at ε = 0.3

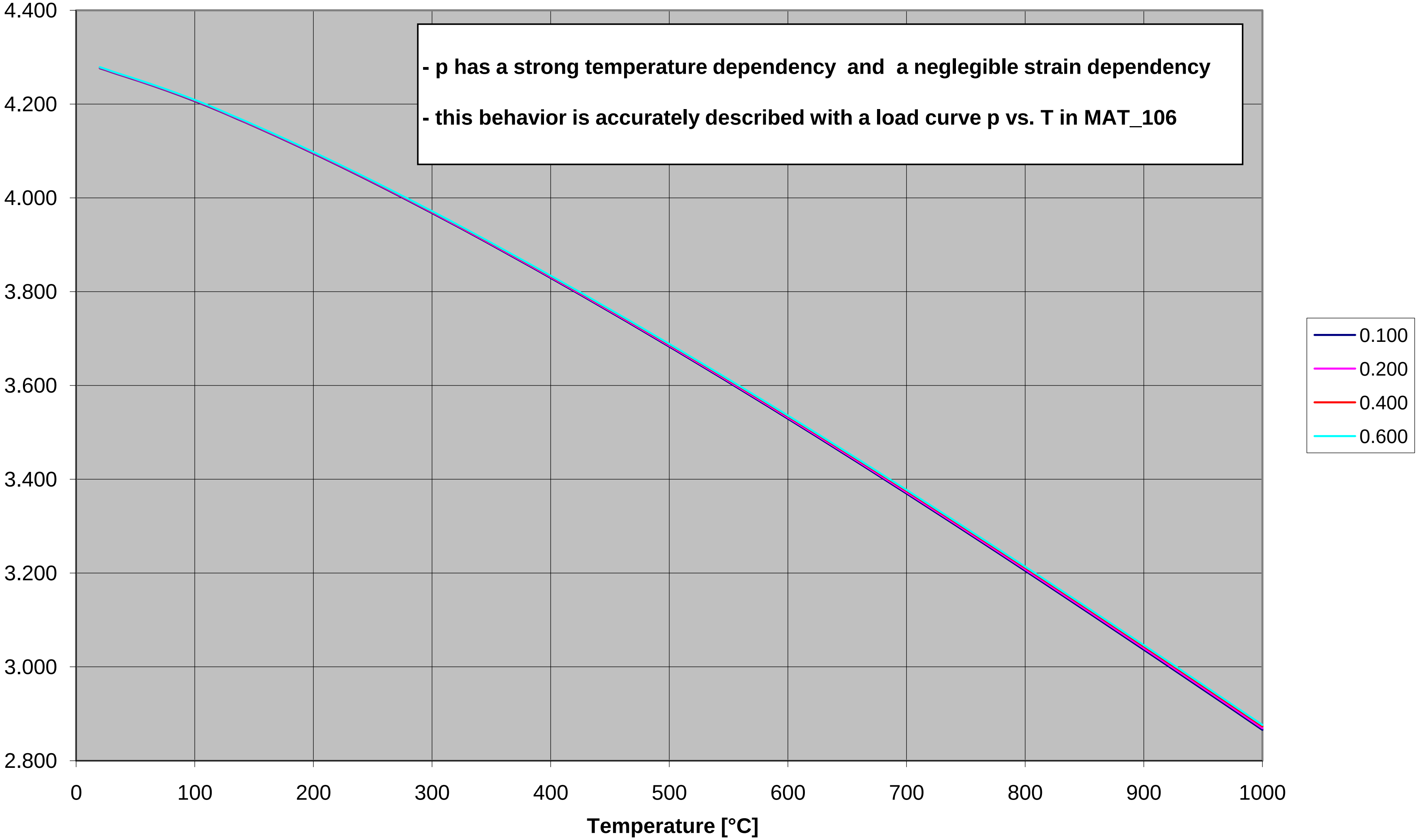
LSTC



MAT_106 : Elastic Viscoplastic Thermal

Parameter p vs. T @ different plastic strains

LSTC



MAT_244 : Ultra High Strength Steel

MAT_244
MAT_UHS_STEEL

This material model is based on the Ph.D thesis by Paul Akerstrom and implemented by Tobias Olsson (ERAB)

Input includes:
1. 15 element constituents
2. Latent heat
3. Expansion coefficients
4. Phase hardening curves
5. Phase kinetic parameters
6. Cowper-Symonds parameters

Output includes:
1. Austenite phase fraction
2. Ferrite phase fraction
3. Pearlite phase fraction
4. Bainite phase fraction
5. Martensite phase fraction
6. Vicker's hardness distribution
7. Yield stress distribution

Paul Akerstrom, "Modelling and Simulation of Hot Stamping", Lulea University of Technology, 2006.

MAT_244 : Ultra High Strength Steel

Material model predicts phase fractions and hardness.

% martensite

Vickers hardness

MAT_244 : Ultra High Strength Steel

Boron steel composition, wt%

	HAZ	Akerstrom	Naderi	ThyssenKrupp Max. values
B		0.003	0.003	0.005
C	0.168	0.23	0.230	0.250
Co				
Mo	0.036			0.250
Cr	0.255	0.211	0.160	0.250
Ni	0.015			
Mn	1.497	1.25	1.18	1.40
Si	0.473	0.29	0.220	0.400
V	0.026			
W				
Cu	0.025			
P	0.012	0.013	0.015	0.025
Al	0.020			
As				
Ti			0.040	0.05
S		0.003	0.001	0.010

MAT_244 : Ultra High Strength Steel

Phase start temperatures

Start temperature calculation algorithm

$T_{ferrite} = A_{e3}$ = 273+912-203C$^{1/2}$-15.2Ni+44.6Si+104Va+31.5Mo-30Mn-11Cr-20Cu+700P+400Al+120As+400Ti

Element wt%

$T_{pearlite} = A_{e1}$ = 273+723-10.7Mn-16.9Ni+29Si+16.9Cr+290As+6.4W

$T_{bainite}$ = 273+ 656-58C-35Mn-75Si-15Ni-34Cr-41Mo

$T_{martensite}$ = 273+561-474C-35Mn-17Ni-17Cr-21Mo

Temperature initial condition must be greater than $T_{ferrite}$

Data printed to D3HSP file and messag file

```
Ferrite    start temperature       = 1.06986E+03
Pearlite   start temperature       = 9.94761E+02
Bainite    start temperature       = 8.43146E+02
Martensite start temperature       = 6.80303E+02
```

http://www.msm.cam.ac.uk/map/kinetics/programs/haz_microstructure.html

MAT_244 : Ultra High Strength Steel

Phase change kinetics

austenite to ferrite

$$\frac{dX_f}{dt} = \frac{\exp\left(-\frac{Q_f}{RT}\right)}{C_f} 2^{(G-1)/2} (\Delta T)^3 X_f^{2(1-X_f)/3} (1-X_f)^{2X_f/3}$$

$C_f = 59.6Mn + 1.45Ni + 67.7Cr + 24.4Mo + K_f B$

austenite to pearlite

$$\frac{dX_p}{dt} = \frac{\exp\left(-\frac{Q_p}{RT}\right)}{C_p} 2^{(G-1)/2} (\Delta T)^3 D X_p^{2(1-X_p)/3} (1-X_p)^{2X_p/3}$$

$C_p = 1.79 + 5.42(Cr + Mo + 4MoNi) + K_p B$

Input parameters

- Q_f = activation energy
- Q_p = activation energy
- Q_b = activation energy
- G = grain size
- α = material constant
- K_f = boron factor
- K_p = boron factor

MAT_244 : Ultra High Strength Steel

Phase change kinetics

LSTC

austenite to bainite

$$\frac{dX_b}{dt}=\frac{\exp\left(-\frac{Q_b}{RT}\right)}{C_b}2^{(G-1)/2}\left(\Delta T\right)^2 DX_b^{2(1-X_b)/3}(1-X_b)^{2X_b/3}$$

$C_b = 10^{-4}(2.34 + 10.1C + 3.8Cr + 19Mo)Z$

austenite to martensite

$$X_m = X_a\left[1-e^{-\alpha\left(T_{ms}-T\right)}\right]$$

Empirical equation with $\alpha = 0.011$

A.J. Fletcher, <u>Thermal Stress and Strain Generation in Heat Treatment</u>, 1989, ISBN 1-85166-245-6.

MAT_244 : Ultra High Strength Steel

Hardeness calculation is empirically based

LSTC

$$H = (x_f+x_p)H_{f\text{-}p} + x_bH_b + x_aH_a$$

$$H_{f\text{-}p} = 42 + 223C + 53Si + 30Mn + 12.6Ni + 7Cr + 19Mo + (10 - 19Si + 4Ni + 8Cr + 130V)\ \ln(dT/dt)_{973}$$

$$H_b = -323 + 185C + 330Si + 153Mn + 65Ni + 144Cr + 191Mo + (89 + 53C - 55Si - 22Mn - 10Ni - 20Cr - 33Mo)\ \ln(dT/dt)_{973}$$

$$H_a = 127 + 949C + 27Si + 11Mn + 8Ni + 16Cr + 12\ \ln(dT/dt)_{973}$$

MAT_244 : Ultra High Strength Steel

Mechanical & Plasticity Material Model

Since the material has 5 phases, the yield stress is represented by a mixture law

$$\sigma_y = x_1\sigma_1\left(\bar{\varepsilon}_1^{\,p}\right) + x_2\sigma_2\left(\bar{\varepsilon}_2^{\,p}\right) + x_3\sigma_3\left(\bar{\varepsilon}_3^{\,p}\right) + x_4\sigma_4\left(\bar{\varepsilon}_4^{\,p}\right) + x_5\sigma_5\left(\bar{\varepsilon}_5^{\,p}\right)$$

LC1
LC2
LC3
LC4
LC5

Where $\sigma_i\left(\bar{\varepsilon}_i^{\,p}\right)$ is the yield stress for phase i at the effective plastic strain for that phase.

References

1. T. Olsson, "An LS-DYNA Material Model for Simulations of Hot Stamping Processes of Ultra High Strength Steels", ERAB, April 2009, tobias.olsson@erab.se
2. P. Akerstrom, Modeling and Simulation of Hot Stamping, Doctoral Thesis, Lulea University of Technology, Lulea, Sweden, 2006.

MAT_244 QA parameter study

	1	2
Q_1/R	11575	13022
Q_2/R	13839	15569
Q_3/R	13588	15287
K_f	1.9e+05	0.
K_p	3.1e+03	0.
a	0.011	0.011
G	8	8

$$[Q/R]_2 = 1.125*[Q/R]_1$$

MAT_244 QA parameter study

LSTC

1

Cooling rate [C/sec]	Vickers Hardness	Ferrite wt%	Pearlite wt%	Bainite wt%	Martensite wt%
200	428	0.0001	0.0010	0.3978	0.5840
100	336	0.0001	0.0031	0.9825	0.0139
40	310	0.0001	0.0188	0.9810	0.0001
20	283	0.0002	0.1193	0.8804	0.0001
10	176	0.0006	0.9993	0.0001	0.0000
5	174	0.0023	0.9976	0.0001	0.0000
2.5	172	0.0125	0.9874	0.0001	0.0000

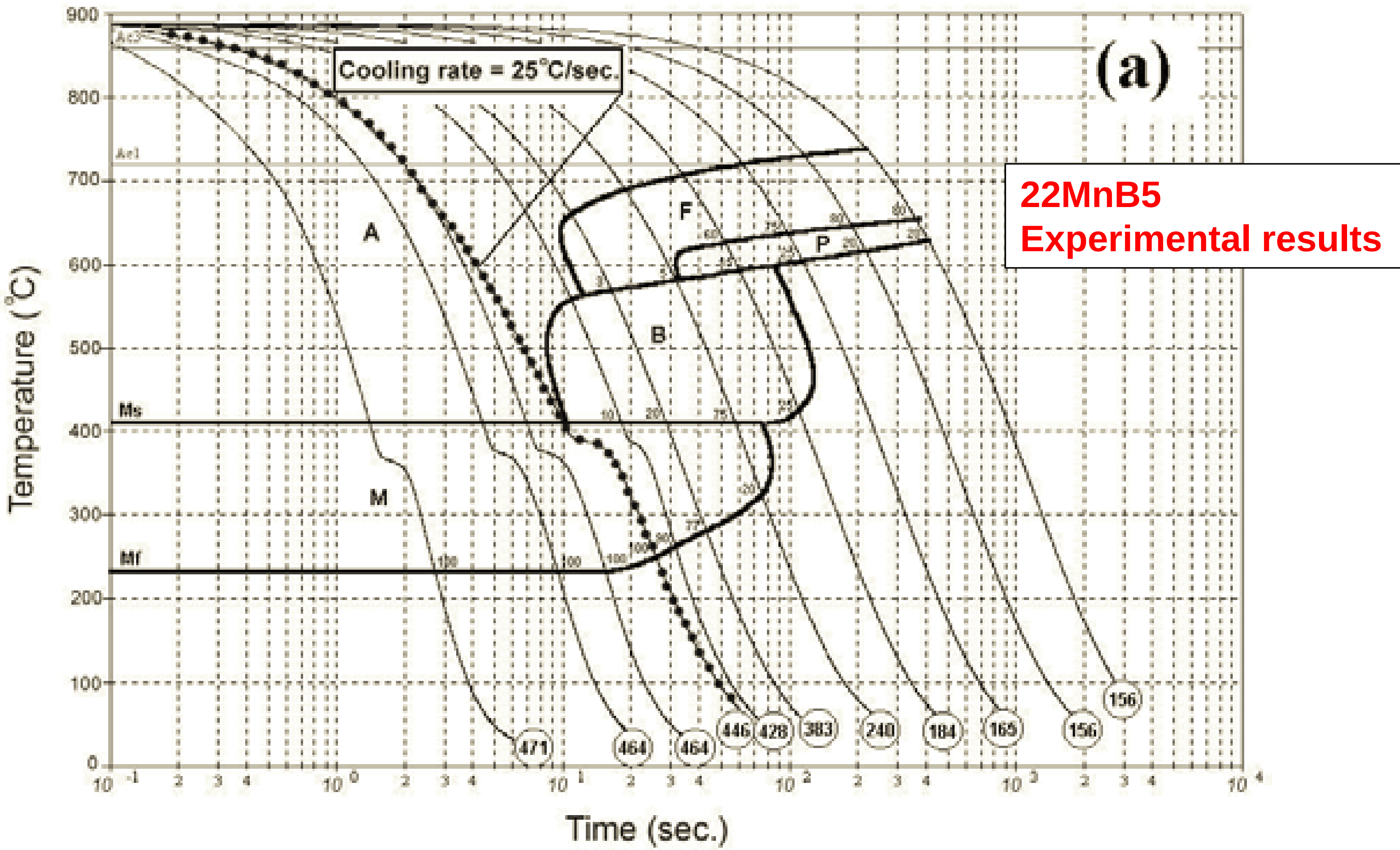
2

Cooling rate [C/sec]	Vickers Hardness	Ferrite wt%	Pearlite wt%	Bainite wt%	Martensite wt%
200	478	0.0001	0.0004	0.0008	0.9692
100	472	0.0001	0.0009	0.0028	0.9668
40	459	0.0002	0.0040	0.0256	0.9416
20	376	0.0005	0.0154	0.4819	0.4880
10	273	0.0018	0.0852	0.9015	0.0111
5	174	0.0093	0.9906	0.0001	0.0000
2.5	172	0.7023	0.2976	0.0000	0.0000

MAT_244 QA parameter study

M. Naderi, Thesis 11/2007, Dept. Ferrous Metallurgy, RWTH Aachen University, Germany

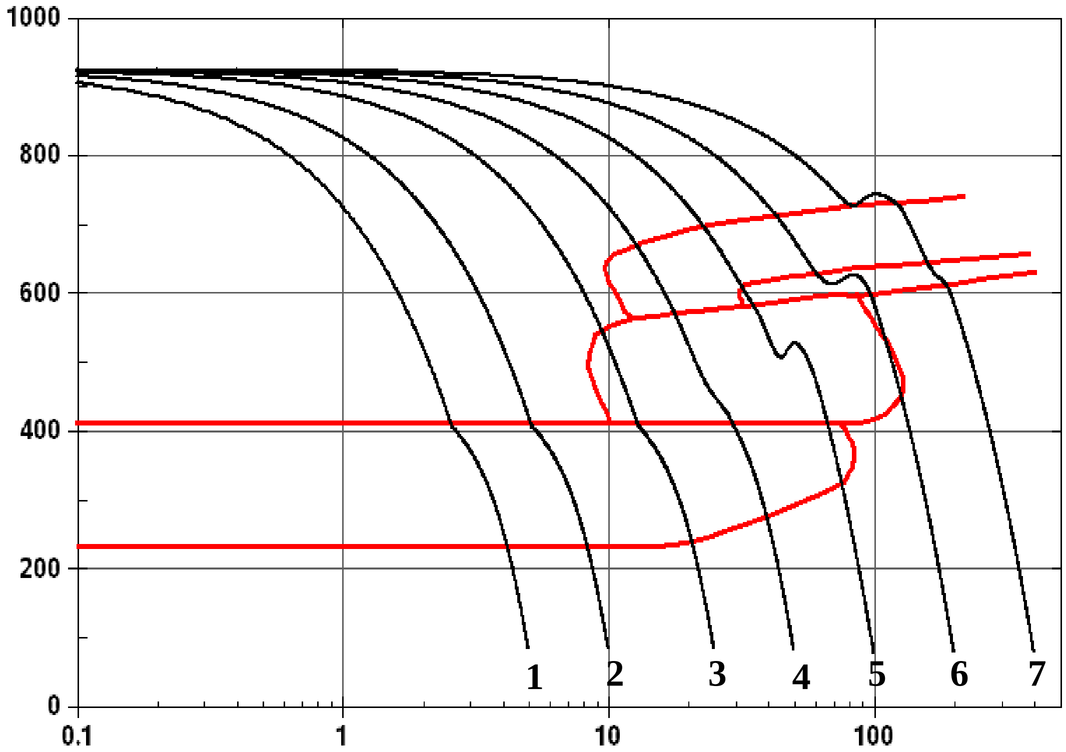
LSTC



MAT_244 QA parameter study

Using data set 2

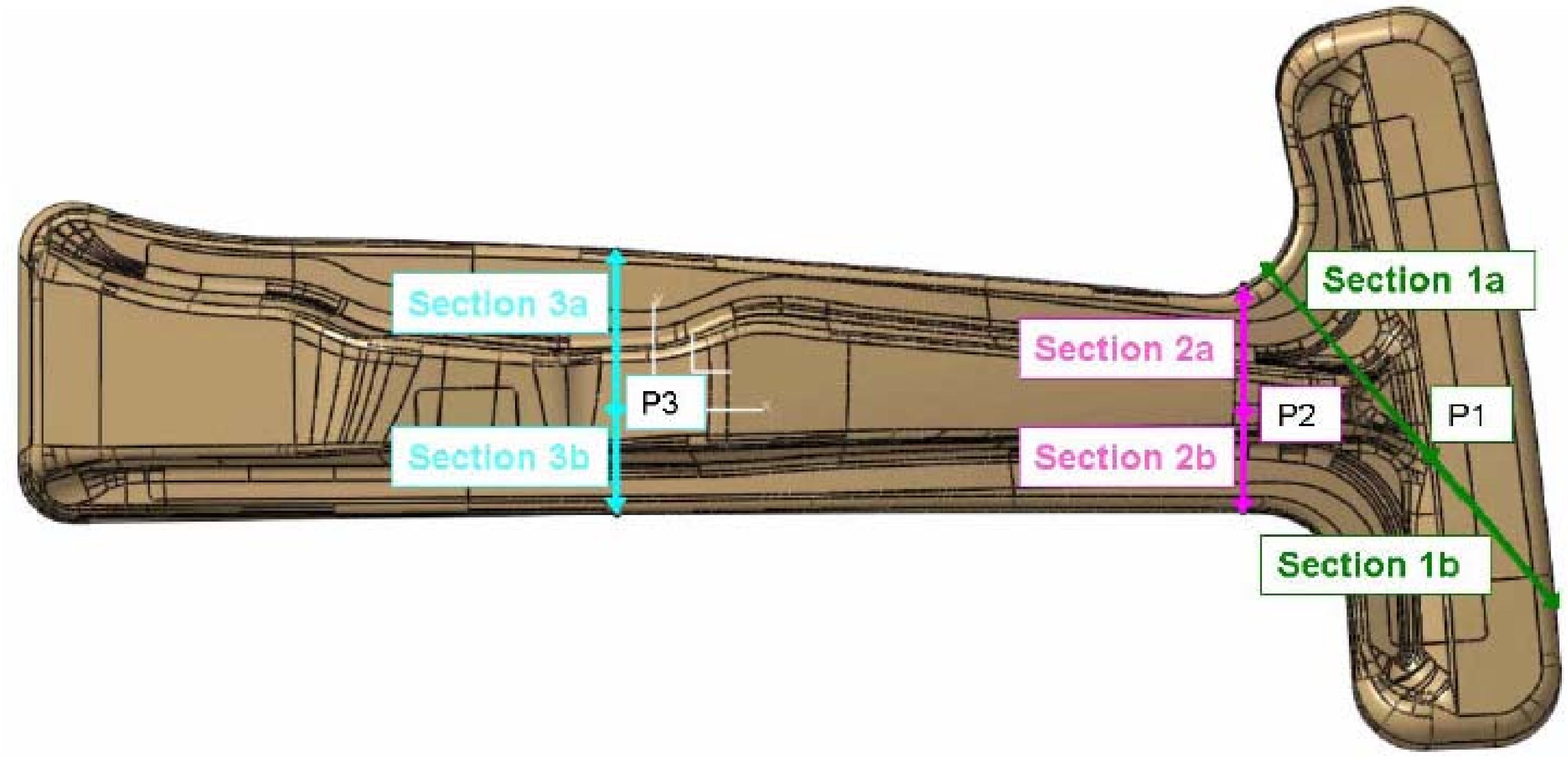
CCT Diagram for 22MnB5 overlaid with LS-DYNA calculated cooling curves and Vickers hardness using MAT_UHS_STEEL



	Rate C/sec	Vickers Hardness	Exp. Naderi
1	200	478	-----
2	100	472	471
3	40	459	428
4	20	376	383
5	10	273	240
6	5	174	175
7	2.5	172	165

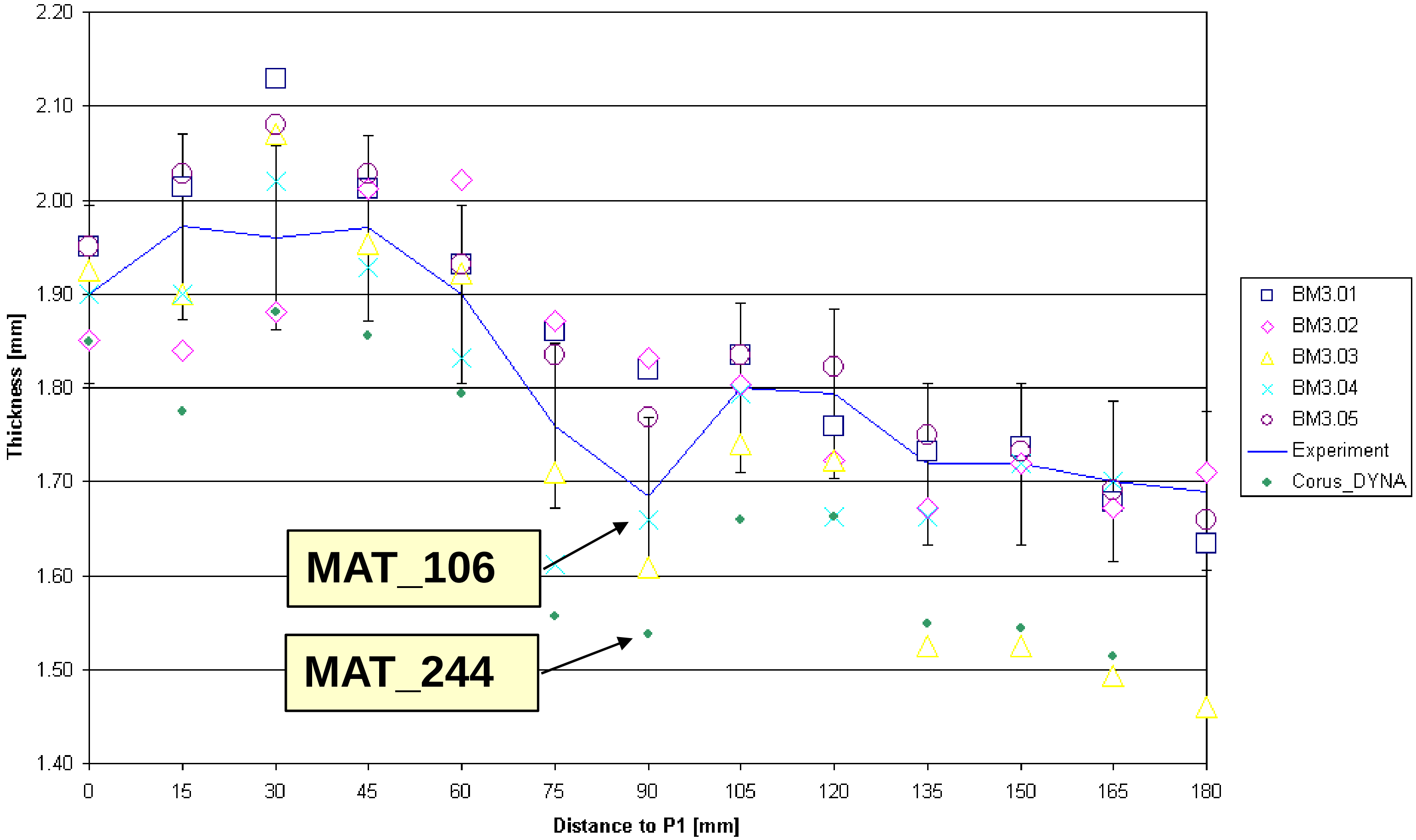
MAT_244 QA parameter study

Numisheet Benchmark BM03



MAT_244 QA parameter study

Numisheet Benchmark BM03 section 1a



By: Sander van der Hoorn, Corus, The Netherlands

MAT_244 QA parameter study

Numisheet BM03 benchmark problem

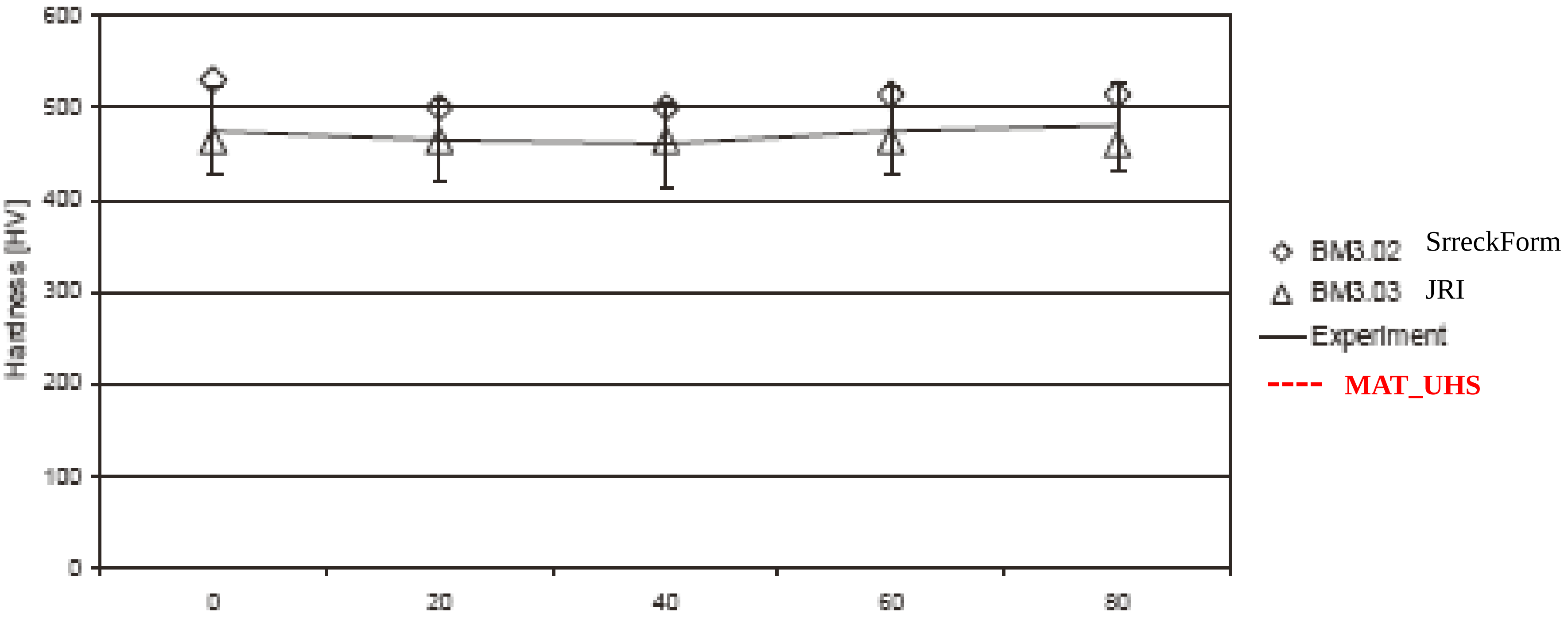
Material model predicts phase fractions and hardness.

% martensite

Vickers hardness

MAT_244 QA parameter study

Vickers hardness for section 2b

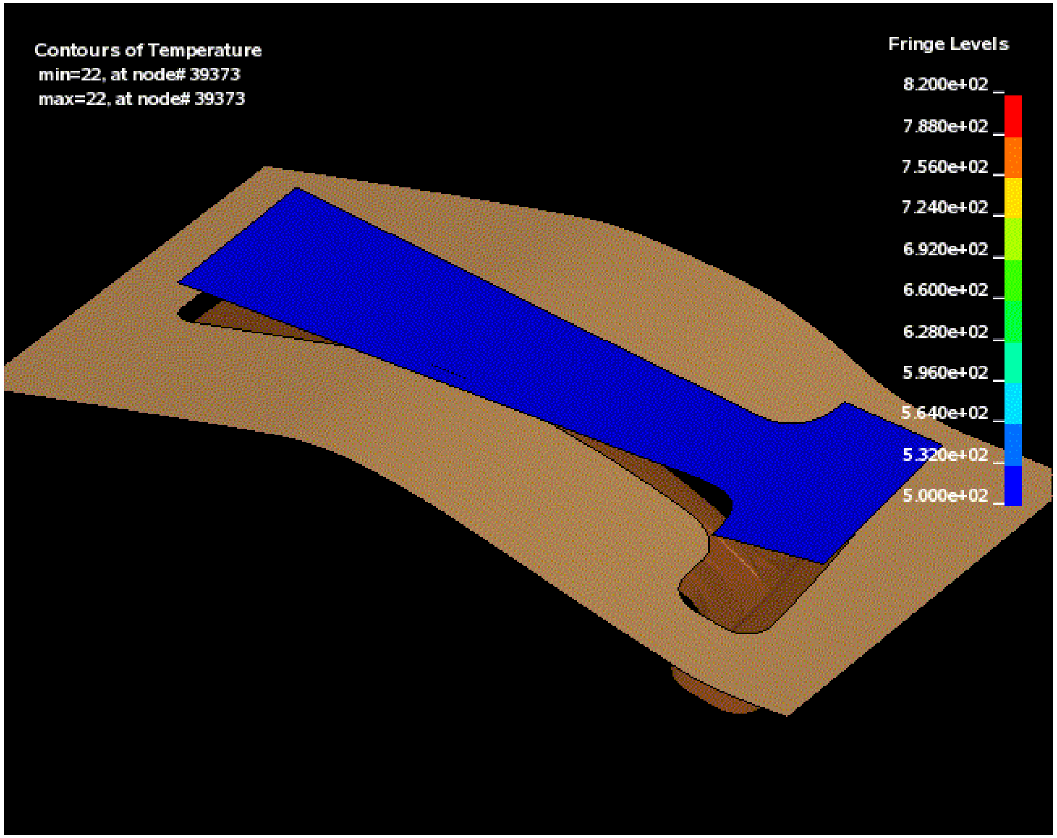


Numisheet 2008 BM03 Model & Simulation

Forming process

FE model

Tools: 68,268 rigid shells
Blank: 3,096 deformable shells increasing to 11,682 after adaptivity



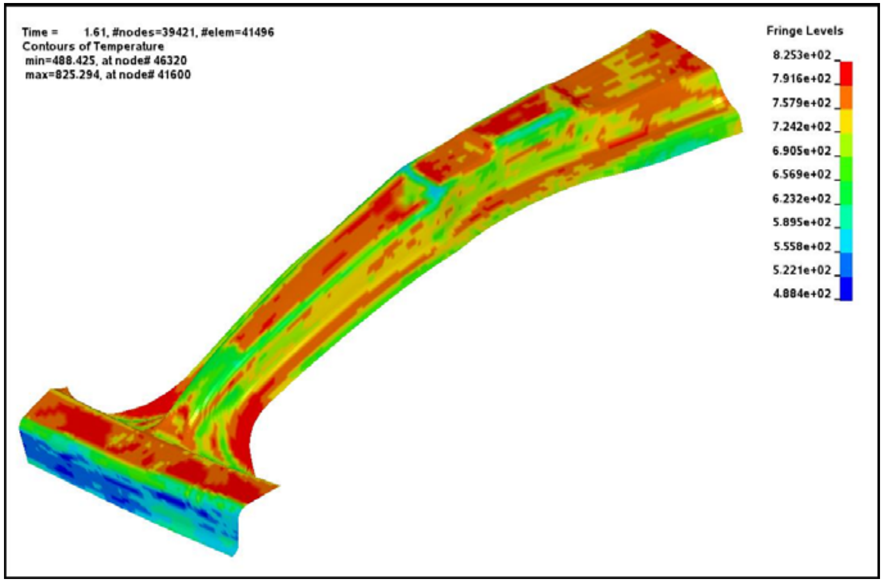
Run time:
INTEL Core Quad CPU @ 2.40GHz

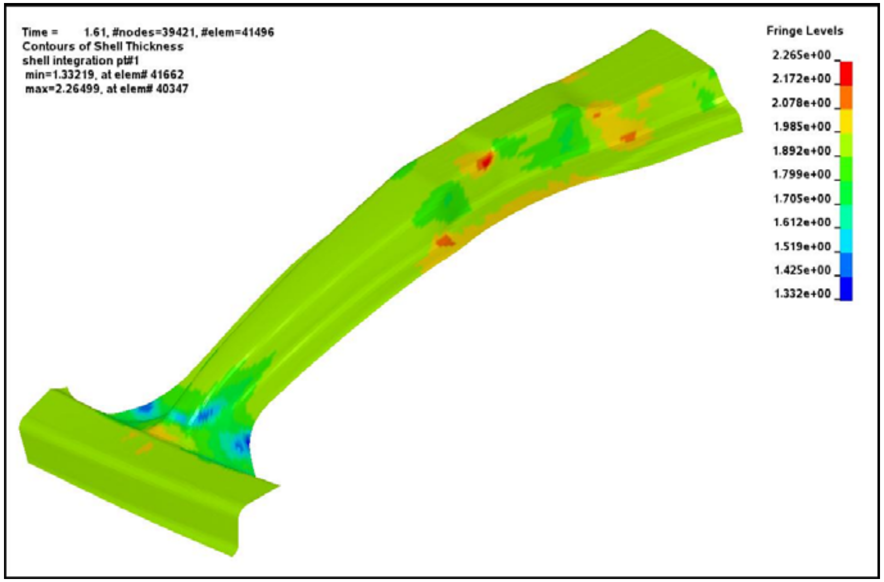
1 cpu → 5.10 hr
2 cpu → 3.96 hr
4 cpu → 2.65 hr

Time step
- **mechanical 1.e-05**
- **thermal 1.e-03**

Numisheet 2008 BM03 Simulation

Results after forming



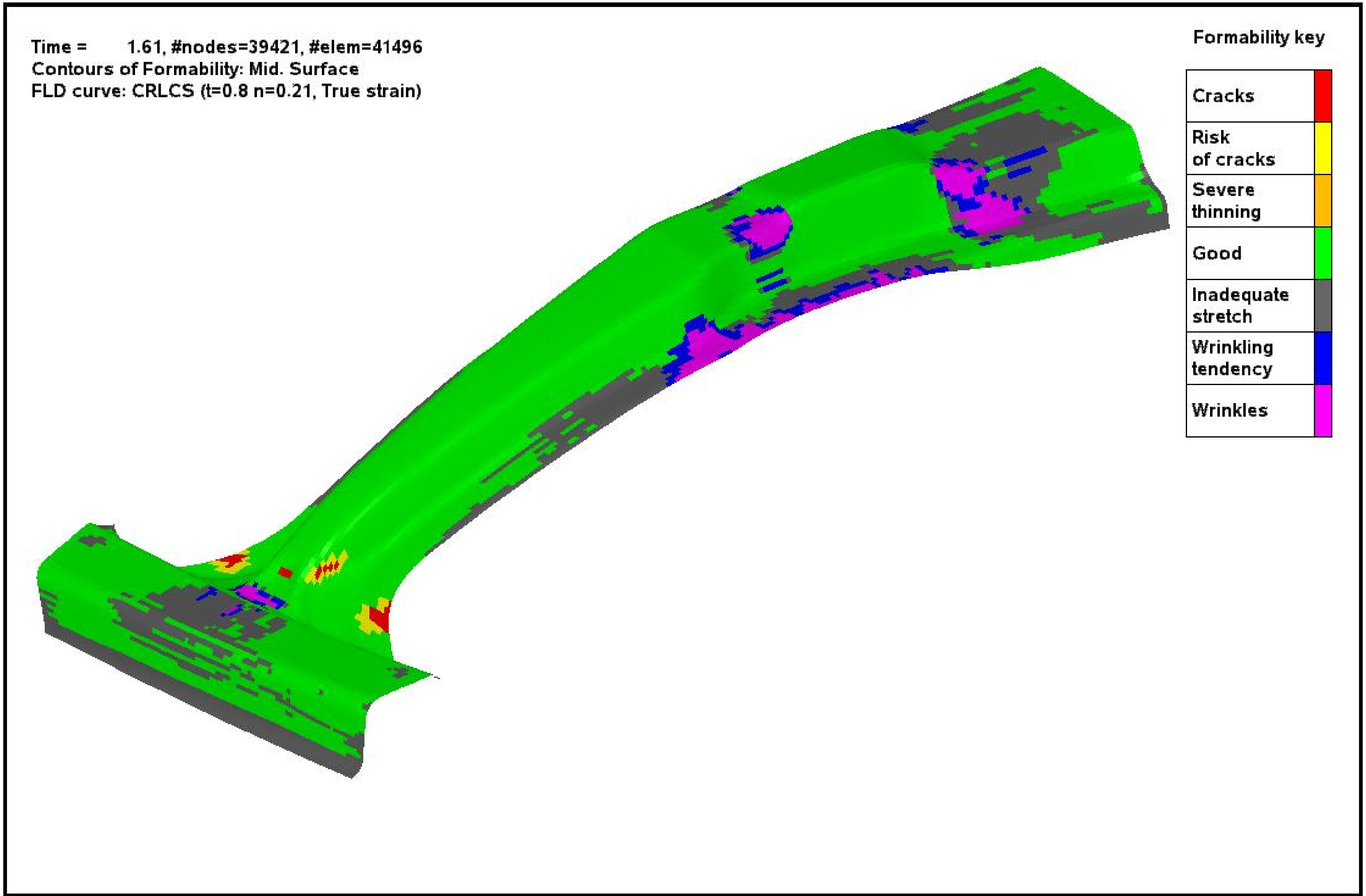


Temperature
min = 488C
max = 825C

Thickness
min = 1.33mm
max = 2.26mm

Numisheet 2008 BM03 Simulation

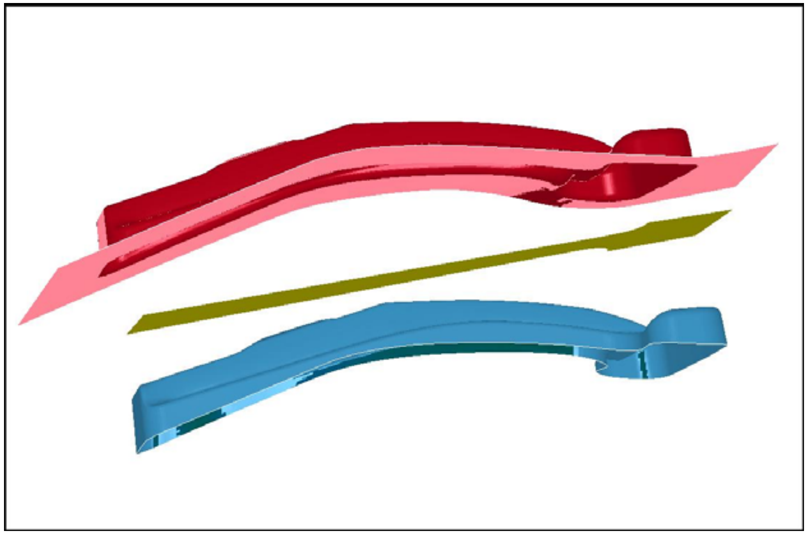
FLD

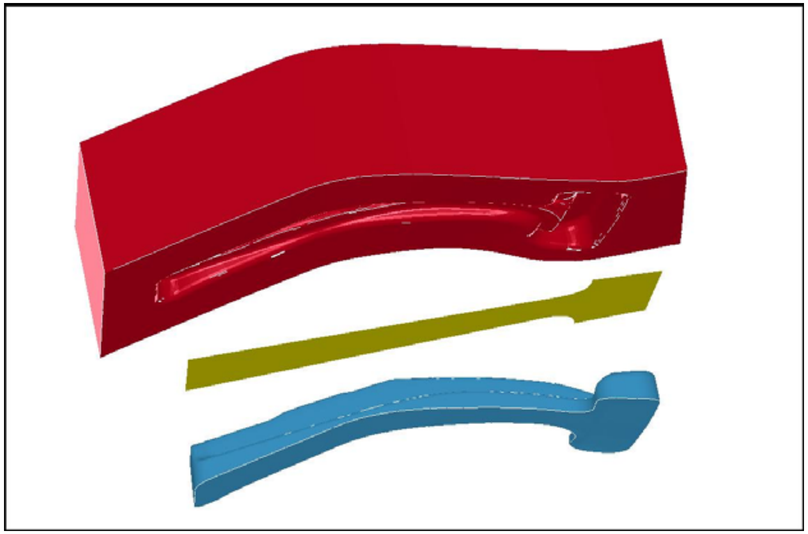


Numisheet 2008 BM03 Simulation

Quench: hold time in the tool 20 sec

Modeling the cooling rate correctly is critical in determining the material phase composition and the material hardness. The local cooling rate is affected by the heat transfer between the blank and tools. The tools must be modeled using solid elements as shown in the figure below for an accurate calculation. We did not do this for the benchmark. Our FE model used shells for the tools fixed at the specified tool temperature of 75C.





shell model dT/dt > solid model dT/dt

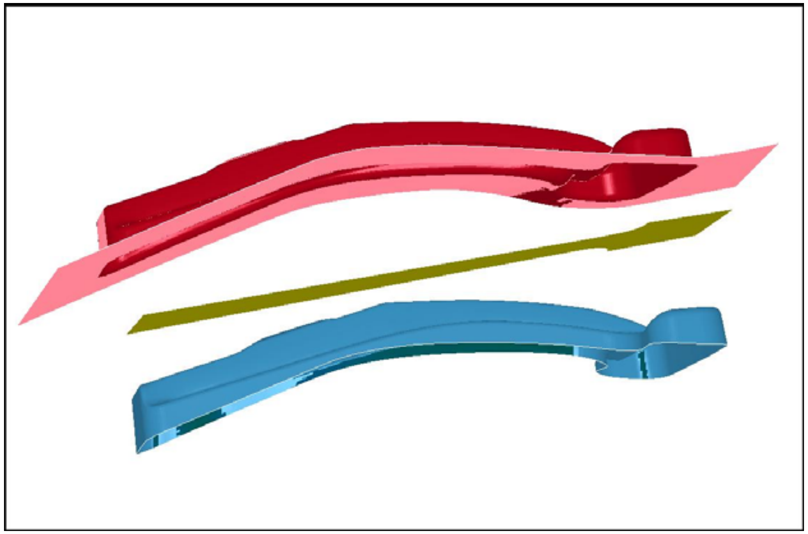
Numisheet 2008 BM03 Simulation

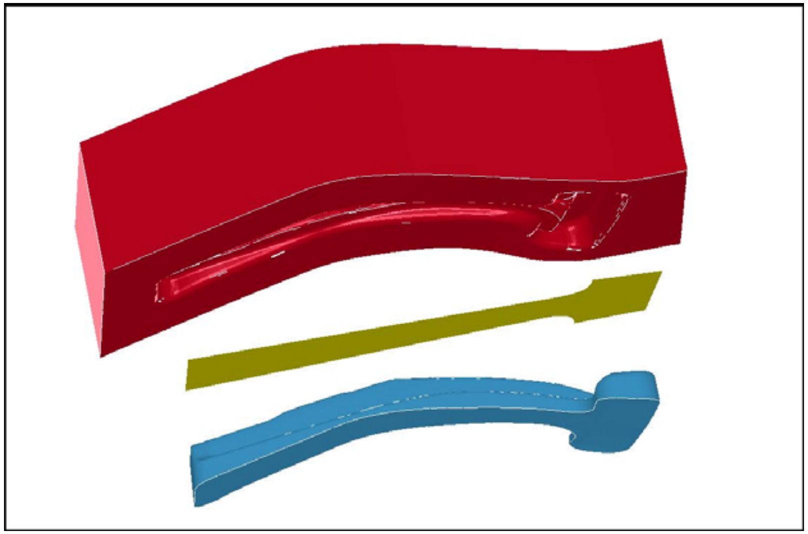
Shell geometry (5.0hr run time)
- 68,268 rigid shells
- 3,096 deformable shells

- 11,682 shells after adaptivity

Solid geometry (5.9hr run time)
- 532,927 solids (punch & die)
- 6,692 shells (holder)
- 3,096 deformable shells (blank)

- 11,682 shells af*ter* adaptivity



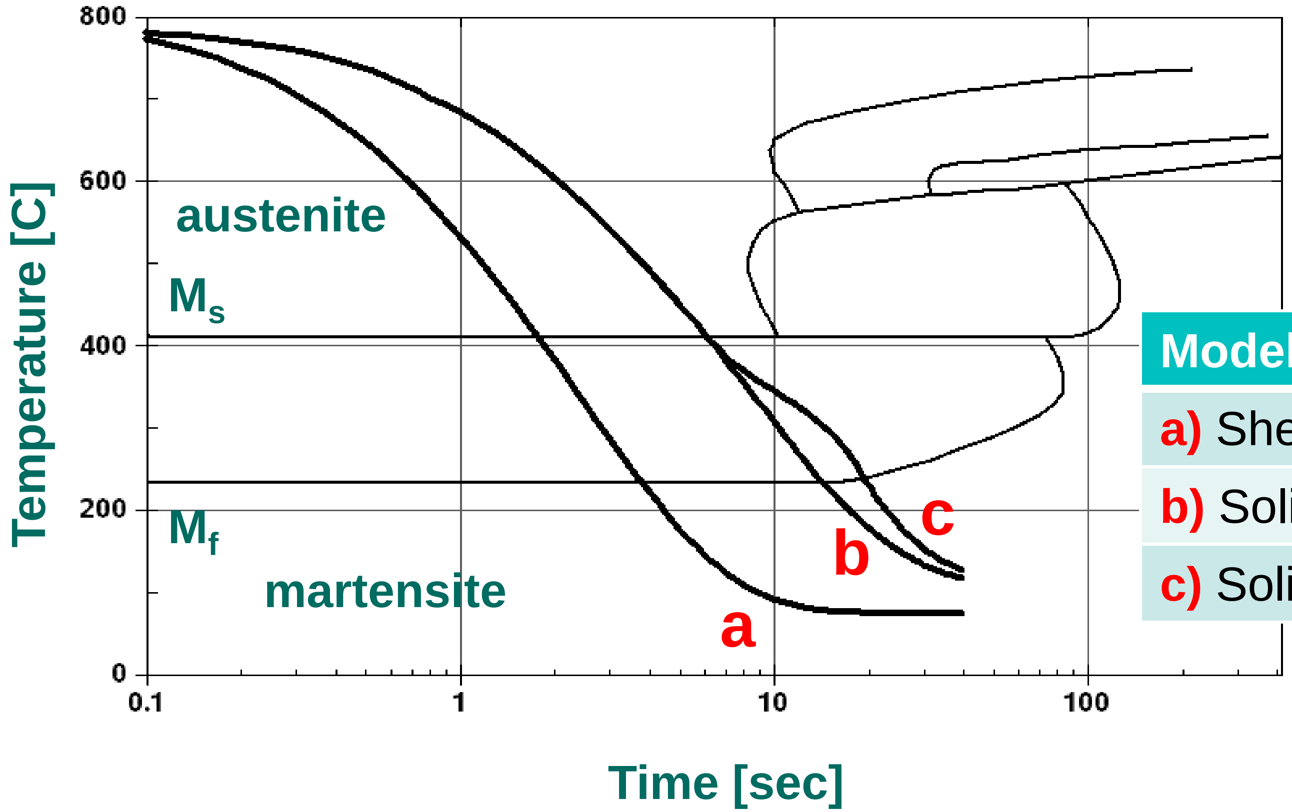


Numisheet 2008 BM03 Simulation

Cool down to room temperature

LSTC

CCT diagram for 22MnB5 steel



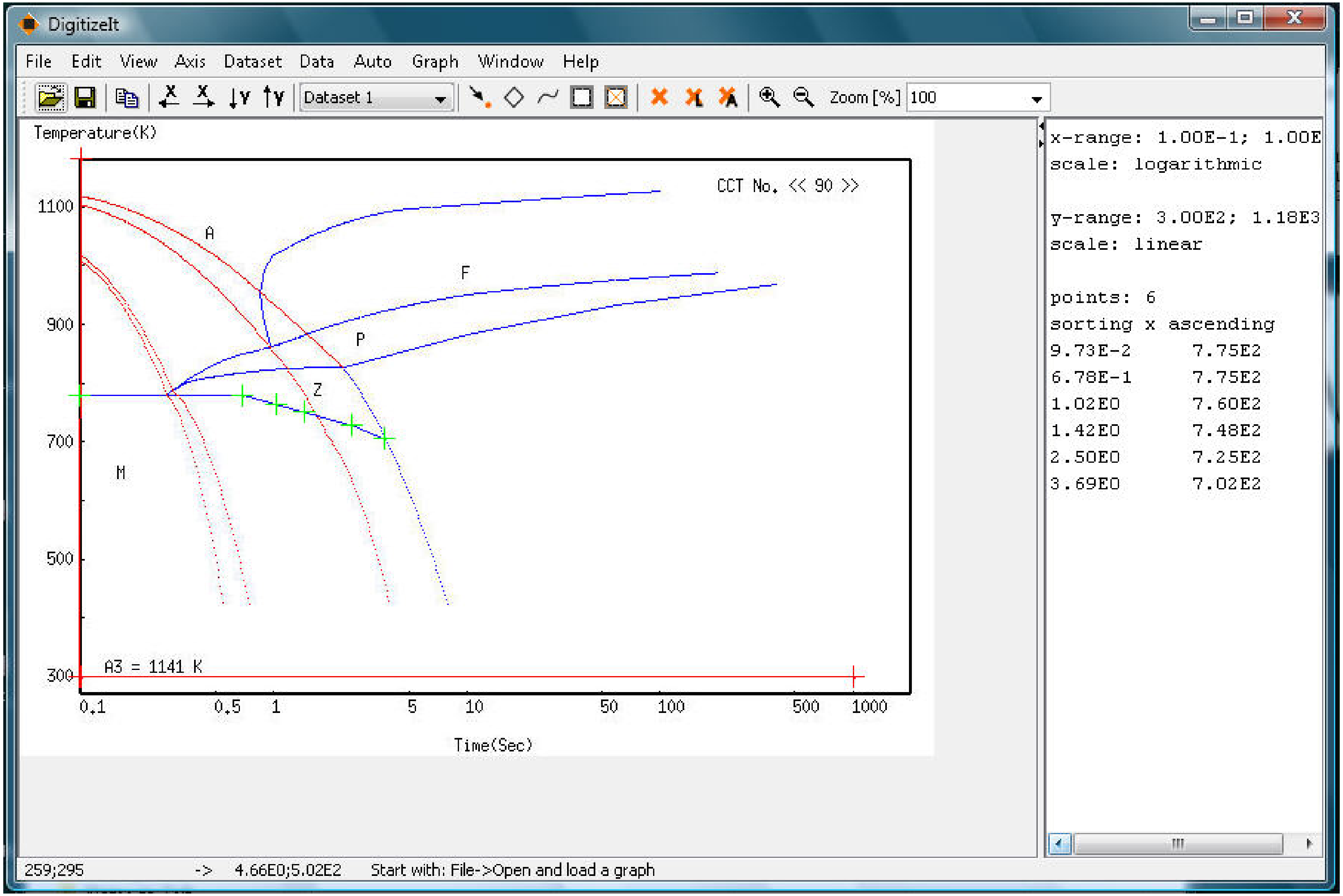
Model
a) Shell tools
b) Solid tools
c) Solid tools + phase change

Our benchmark results are depicted by curve (a). Subsequently, we looked at the affect when using solid tools (b) and including phase change (c). The cooling rate is much slower.

Creating a CCT diagram

DigitizeIt, http://www.digitizeit.de/

LSTC



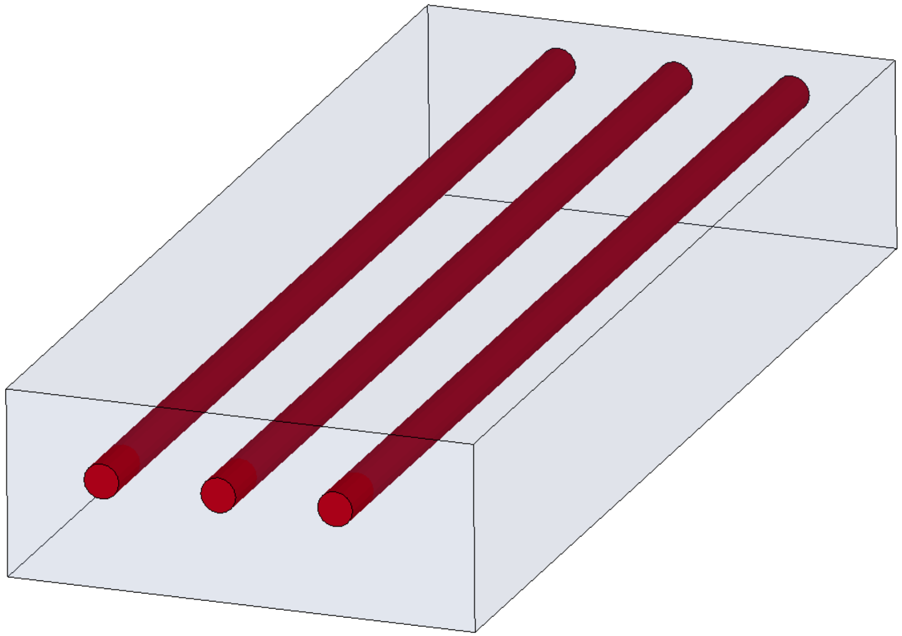
Creating a CCT diagram

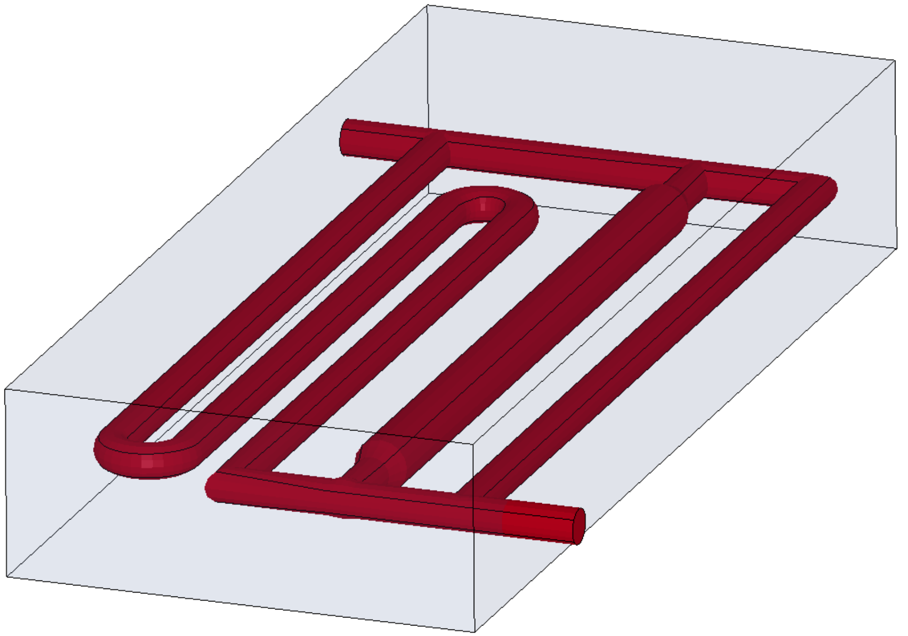
1. Obtain an image of a CCT diagram (e.g., from https://inaba.nims.go.jp/Weld/cct/
2. Use software to digitize curves (e.g, DigitizeIt, http://www.digitizeit.de/) and save as xy-data
3. Using LS-PrePost, plot temperature history of one or more nodes and save as xy-data
4. Import xy-data into LS-PrePost and display curves on a single plot

Modeling tool cooling

There are 2 methods to model fluid flow

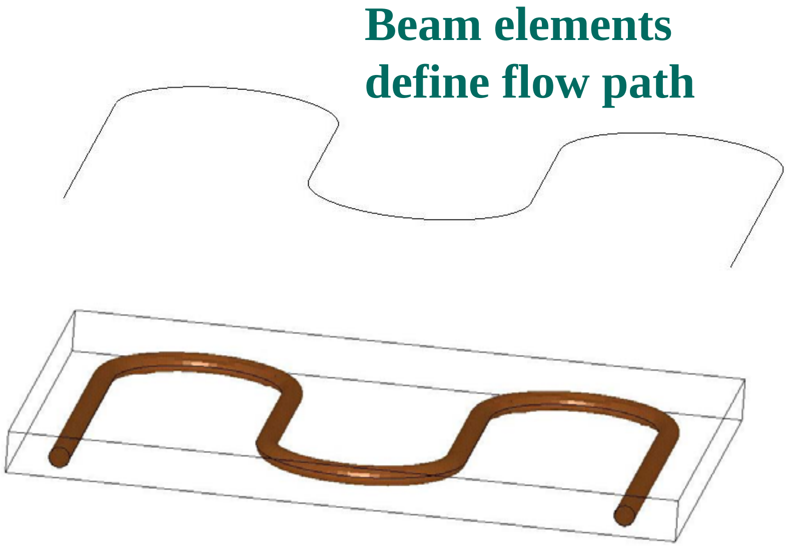
BULKFLOW | **Network Analyzer**

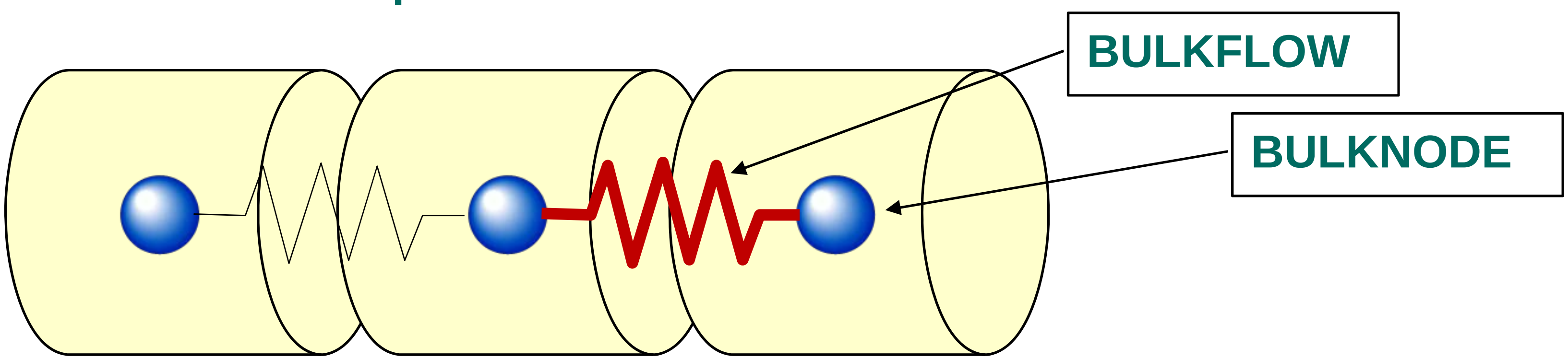




BULKNODE and BULKFLOW method

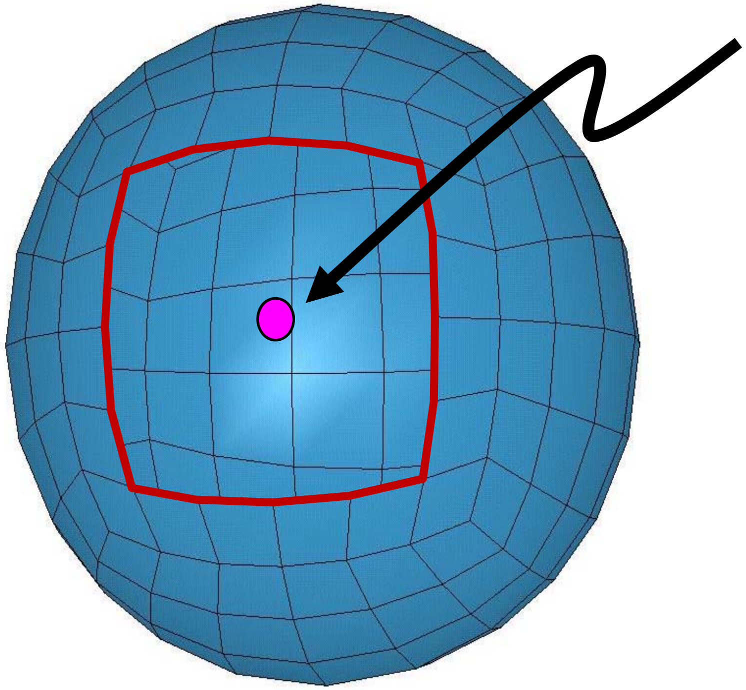
BULK FLOW is a lumped parameter approach to model fluid flow in a pipe. The flow path is defined with a contiguous set of beam elements. The beam node points are called **BULK NODES** and have special attributes in addition to their (x,y,z) location. Each **BULKNODE** represents a homogeneous slug of fluid. Using the **BULKFLOW** keyword we define a mass flow rate for the beams. We then solve the advection-diffusion equation.





BULKNODE – modeling a gas or fluid in a container

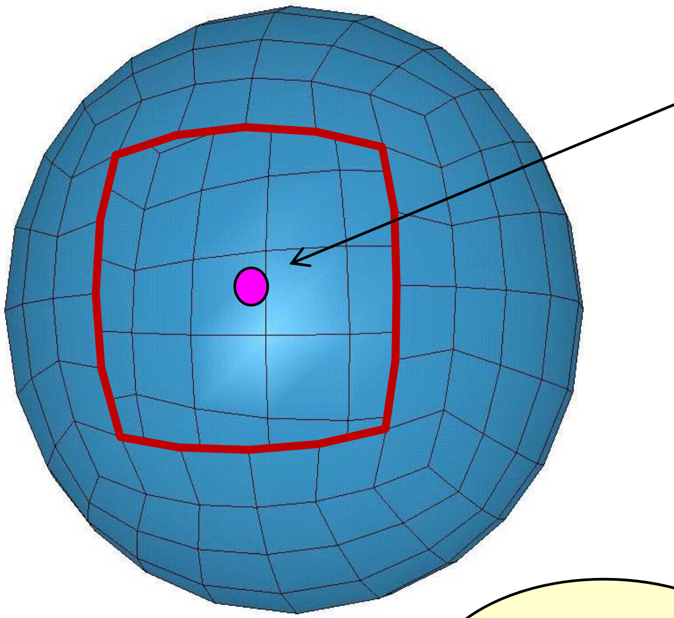
*BOUNDARY_THERMAL_BULKNODE



BULKNODE -This is a lumped parameter approach to model a fluid inside a rigid container. A node is defined with a specified volume, density, and heat capacity. The node coordinates are arbitrary, but it makes sense to place the node in the correct geometric position for visualization. The surface segments of the container are also defined so the bulk node can exchange heat by convection and radiation to the container.

Note that we are not modeling conduction in the fluid. The entire fluid volume is homogeneous at temperature T. The fluid temperature changes due to convection and radiation heat exchange with the container.

BULKNODE – modeling a gas or fluid in a container



The heat flow between the bulk node, B, and the surrounding surface, S, is given by

$$\dot{q}'' = h\left(T_S^a - T_B^a\right)^b$$

The value of h has the greatest uncertainty. The section on "How do you determine h" shows a hand calculation. Or, you may run a CFD code to numerically determine h.

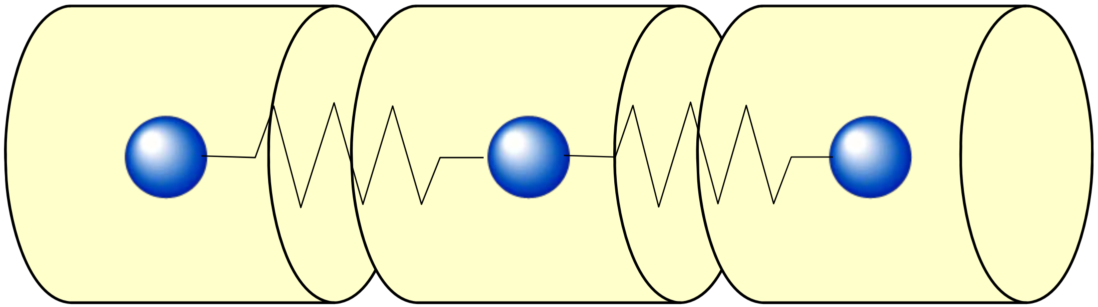
BULKNODE – modeling a gas or fluid in a container

BOUNDARY_THERMAL_BULKNODE keyword


```
*BOUNDARY_THERMAL_BULKNODE
NID   PID   NBNSEG   VOL   LCID   H   A   B
```

NID	bulk node number
PID	this bulk node is assigned a PID which in turn assigns material properties
NBNSEG	number of surface segments surrounding the bulk node
VOL	volume of bulk node (i.e., cavity volume – calculated by LSPP during mesh generation)
LCID	load curve ID for heat transfer coefficient h
H	heat transfer coefficient h
A	exponent a
B	exponent b

BULKFLOW – modeling flow through a pipe



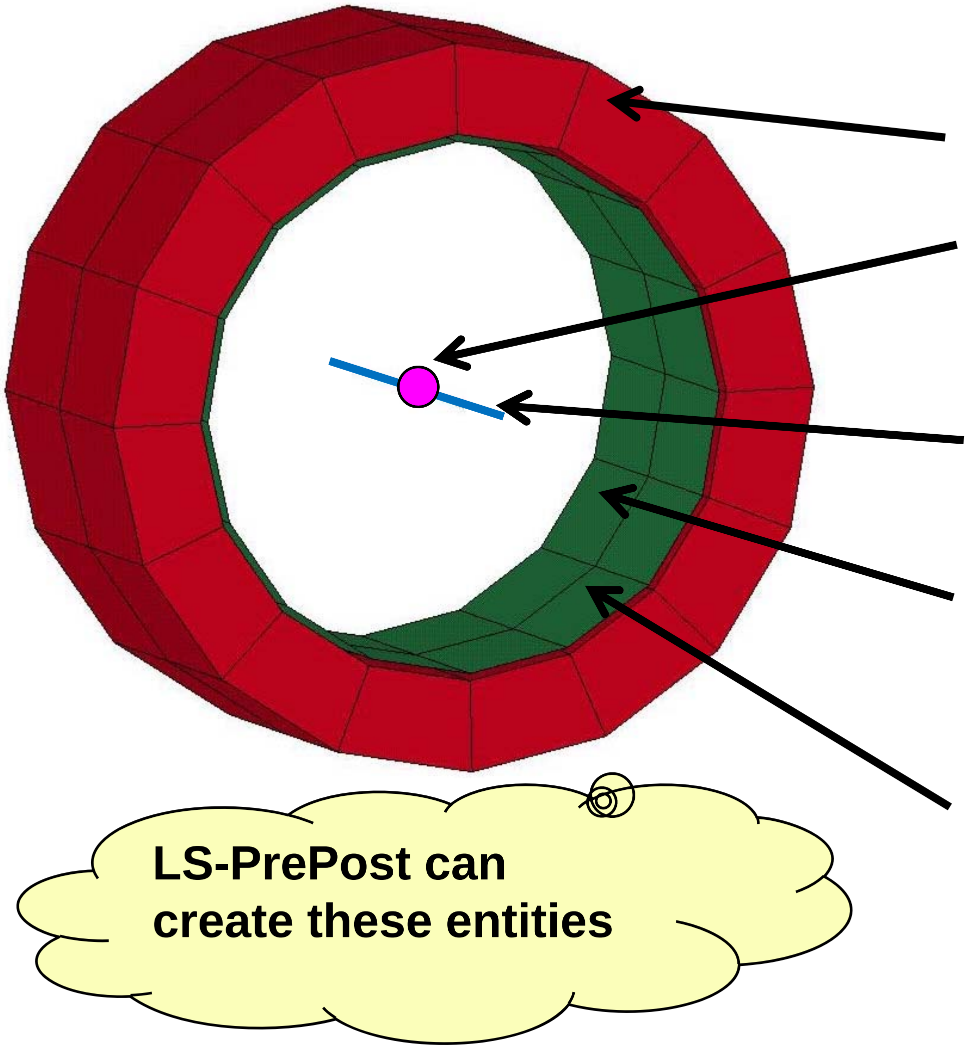
Using the **BULKFLOW** keyword we define a mass flow rate for the beams connecting the **BULKNODES**. We then solve the advection-diffusion equation.

$$\rho c \frac{\partial T}{\partial t} + \rho c V \frac{\partial T}{\partial x} = K \frac{\partial^2 T}{\partial x^2}$$

*BOUNDARY_THERMAL_BULKFLOW_ { ELEMENT / SET }

EID LCID MDOT

Modeling flow through a pipe



Five entities are required

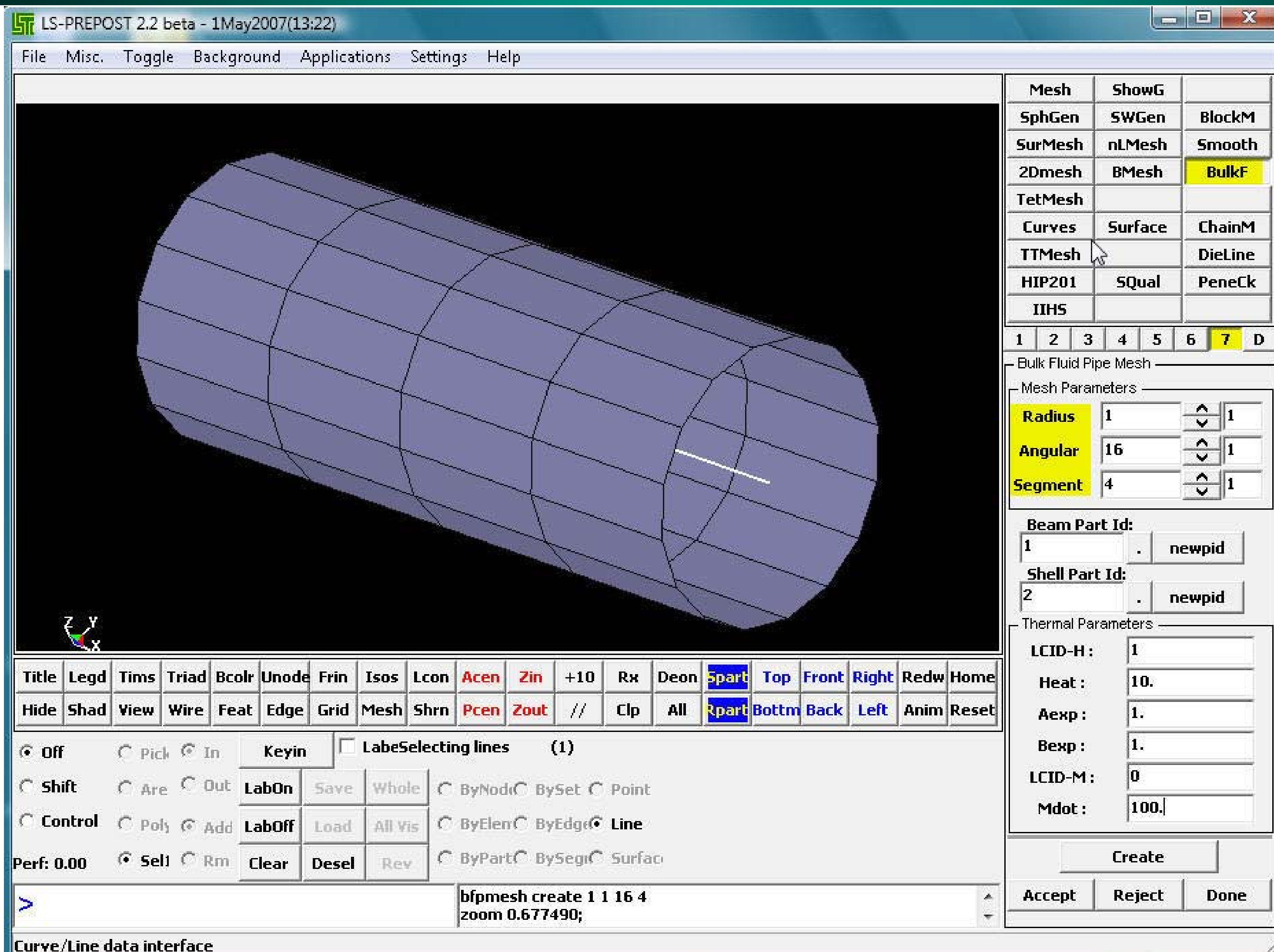
1. Pipe / Die – solid elements.
2. BULKNODE– defines fluid properties, fluid volume and heat transfer to surface layer.
3. BULKFLOW– beam elements define the flow path (centerline of the pipe).
4. Surface layer – shell elements define the outer boundary surface of the fluid.
5. Contact - used to connect dissimilar surface layer to pipe mesh.

Modeling flow through a pipe

Required keywords

Keywords	Purpose
*PART *ELEMENT_SOLID	1. define pipe / die
*PART *BOUNDARY_THERMAL_BULKNODE	2. define bulk node
*PART *ELEMENT_BEAM *BOUNDARY_THERMAL_BULKFLOW_ELEMENT	3. define bulk flow
*PART *ELEMENT_SHELL	4. define surface layer
*CONTACT_SURFACE_TO_SURFACE	5. Fluid structure interaction

Using LS-PrePost to create BULKNODE & BULKFLOW keywords



Bulk flow button

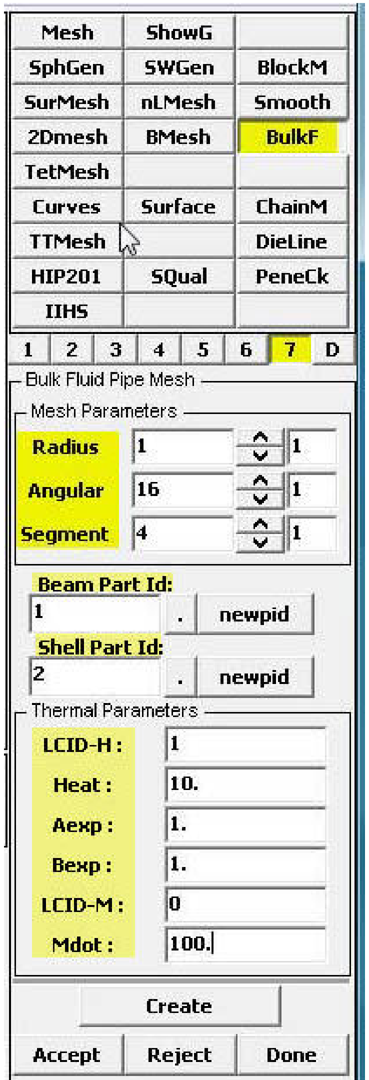
Screen 7

Mesh

Part definitions

Fluid structure interaction

Using LS-PrePost to create BULKNODE & BULKFLOW keywords



Bulk flow button

Screen 7

Generate mesh
- **radius of pipe**
- **number of angular segments**
- **number of axial segments**

Beam PID - used to associate fluid material properties to the BULKFLOW elements.

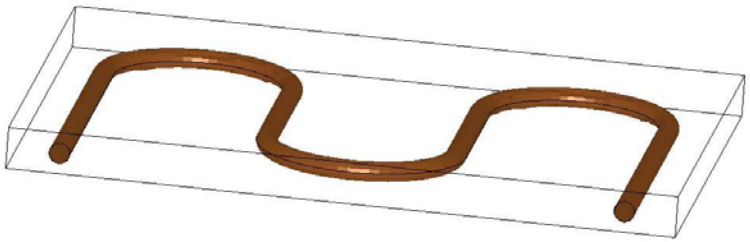
Shell PID - used to associate fluid material properties to the BULKNODES and shell outer surface layer.

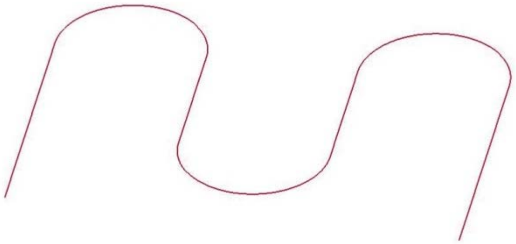
Fluid structure interaction $\dot{q}'' = h\left(T_s^{\,a} - T_b^{\,a}\right)^b$

Fluid mass flow rate

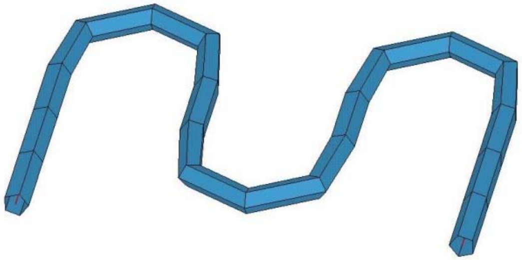
Using LS-PrePost to create BULKNODE & BULKFLOW keywords

Shown is a serpentine flow channel passing through a die

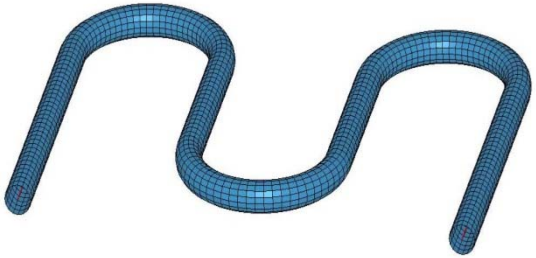




Curve defining flow path



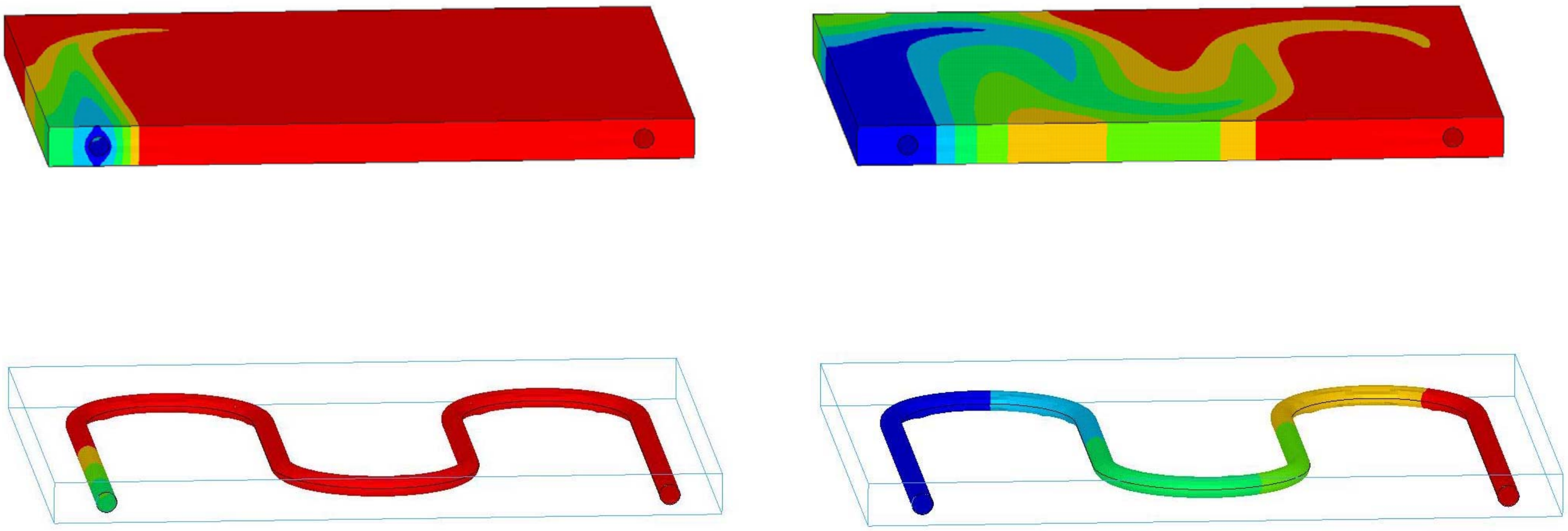
Radial 5
Axial 20



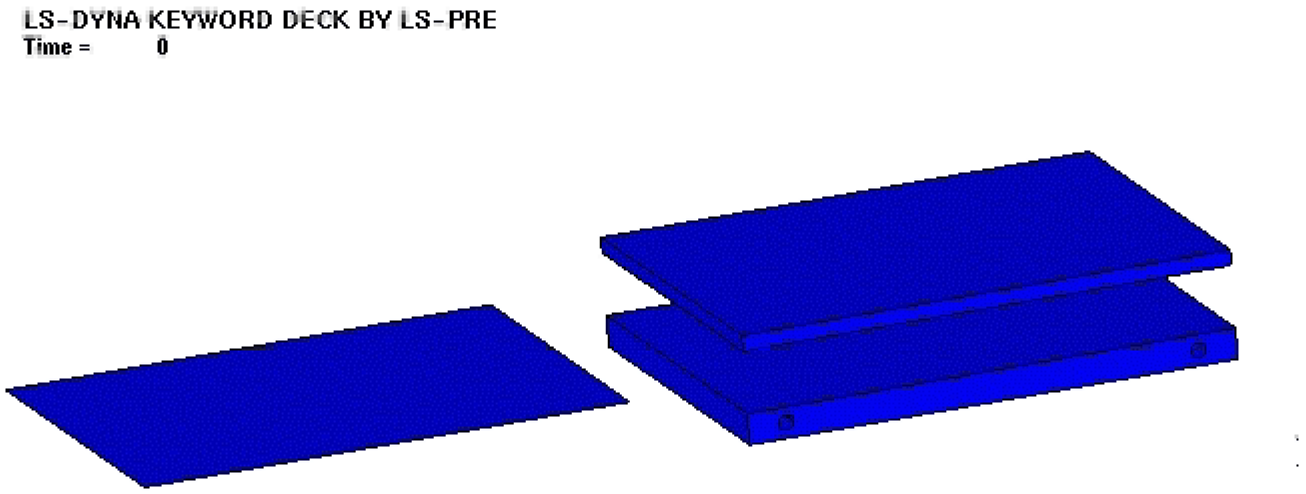
Radial 16
Axial 200

Application – die cooling

A Bulk Fluid Flow algorithm is used to model the energy exchange between the cold fluid flowing through the die cooling channels.



Application – die cooling



Water properties

T [C]	ρ [kg/m^3]	C_p [J/kg C]	μ [kg/m s]	k [W/m C]
20	998.	4182.	1.002e-03	0.603
40	992.	4179.	0.651e-03	0.632
60	983.	4185.	0.462e-03	0.653
80	972.	4197.	0.350e-03	0.670
100	958.	4216.	0.278e-03	0.681

Problem definition

Pipe diameter = D = 15mm = 0.015 m

Pipe cross section area = A = $\pi D^2/4 = \pi(0.015)^2/4$ = 1.77e-04 m^2

Volumetric flow rate = G = 20 l/min = 0.02 m^3/min = 3.33e-04 m^3/sec

Flow velocity = G/A = 1.89 m/sec

Pipe wall temperature = T_{wall} =100C

Water temperature = T_{fluid} = 20C

Some preliminaries

Fully developed – the effect of entrance conditions (e.g., pipe from a header) on h are negligible.

$$\frac{L}{D} > 40$$

Fluid properties are evaluated at the film temperature, T_{film}

$$T_{film} = \frac{T_{wall} + T_{fluid}}{2} = \frac{100 + 20}{2} = 60$$

Reynolds number

$$\mathrm{Re} = \frac{V\rho D}{\mu} = \frac{(1.89)(983)(0.015)}{0.462*10^{-3}} = 6.03*10^{4}$$

Prandtl number

$$\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{(4185.)(0.462*10^{-3})}{0.653} = 2.96$$

Classical empirical correlations

Dittus-Boelter equation

$$h = 0.023\frac{k}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$$

n=0.3 for cooling of the fluid
n=0.4 for heating of the fluid

$$= 0.023\frac{0.653}{0.015}\left(6.03*10^{4}\right)^{0.8}\left(2.96\right)^{0.4} = 10,300\ \frac{W}{m^{2}C}$$

What do you do if the pipe is not perfectly smooth

Sieder-Tate equation

$$h = 0.023\frac{k}{D}\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}\left(\frac{\mu_{bulk}}{\mu_{wall}}\right)^{0.14}$$

μ(T) correction factor

How do you determine a pipe flow convection coefficient

Gnielinski correlation

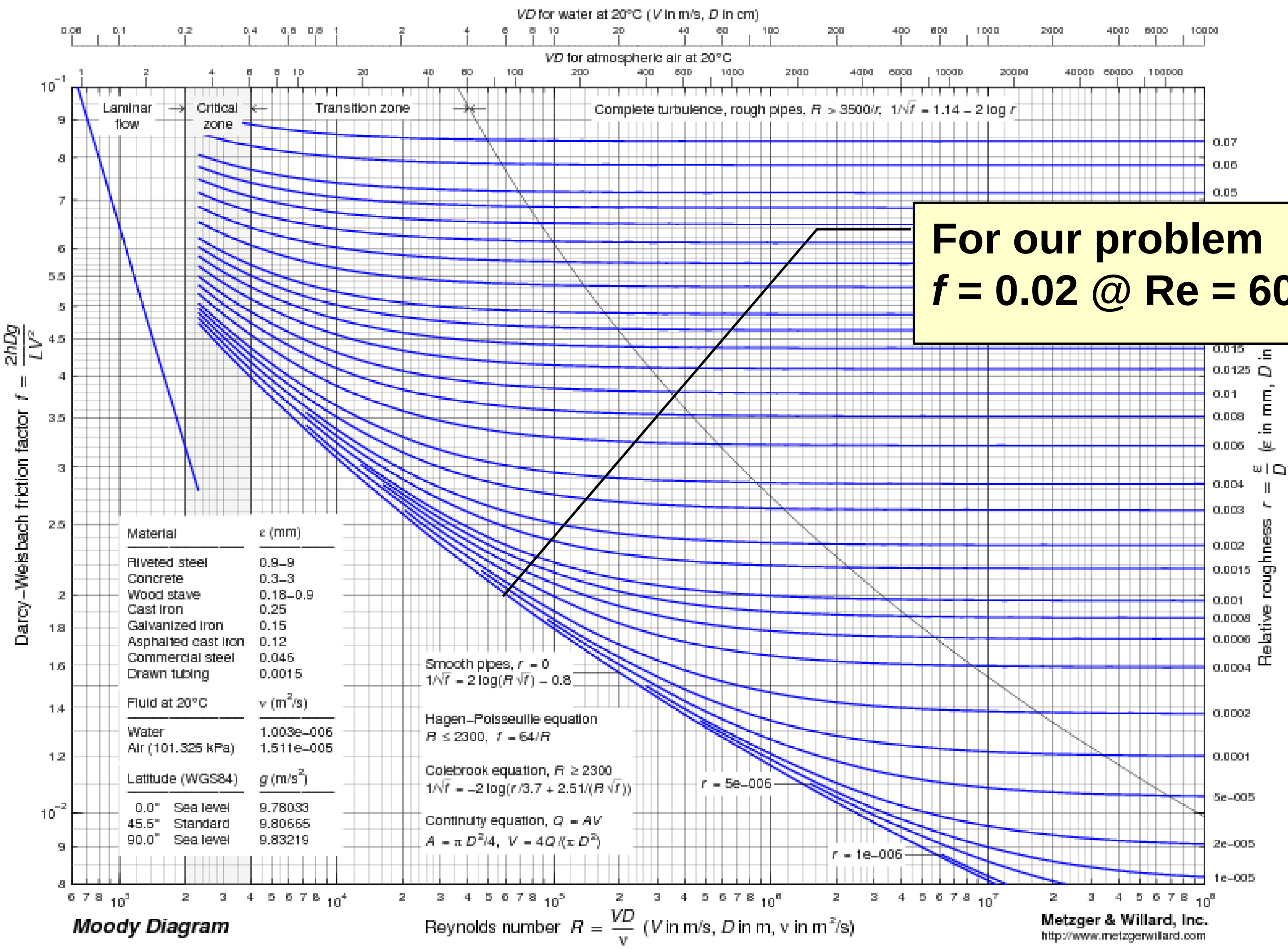
$$h = \left(\frac{k}{D}\right)\left[\frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1+12.7(f/8)^{0.5}\left(\mathrm{Pr}^{2/3}-1\right)}\right] = 11{,}400\ W/m^2C$$

f **= Darcy–Weisbach friction factor (see next vu-graph for value)**

There are 2 definitions for *f*. The Darcy–Weisbach friction factor is 4 times larger than the Fanning friction factor, so attention must be paid to note which one of these is meant in any "friction factor" chart or equation being used. The Darcy–Weisbach factor is more commonly used by civil and mechanical engineers, and the Fanning factor by chemical engineers, but care should be taken to identify the correct factor regardless of the source of the chart or formula.

How do you determine a pipe flow friction factor

http://www.mathworks.com/matlabcentral/fx_files/7747/1/moody.png



For our problem
f = 0.02 @ Re = 60,300

Workshop problem: Advection – Diffusion

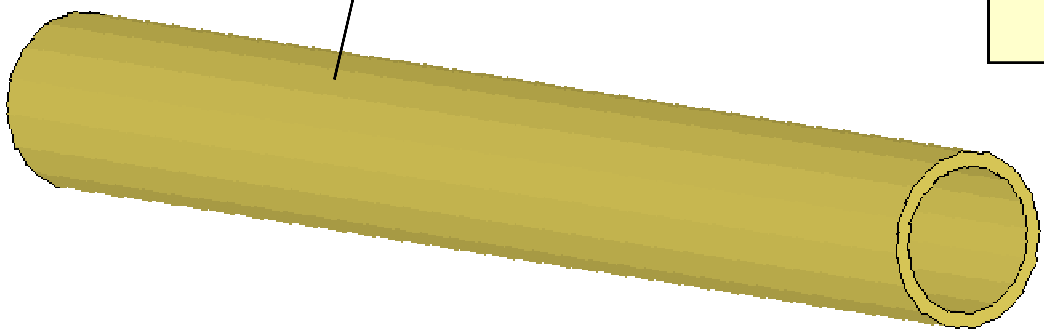
pipe.k

Consider steady state 1-dimensional bulk fluid flow through a pipe

Entry temperature
$T_2 = 2$

Pipe size
dia=0.01, length=1.

Exit temperature
$T_1 = 1$



Fluid properties

$k = \rho = c = 1$

Fluid velocity

v=1

The inner pipe wall is fixed at T = 0. The flowing fluid loses heat by convection to the pipe with h = 0.005

Workshop problem: Advection – Diffusion

pipe.k

Pipe geometry

x = half length = 0.5

d = diameter = 0.01

p = perimeter = pd =0.0314

A = cross sectional area = pd^2 /4= $7.85*10^{-5}$

Fluid data

r = density = 1.

k = thermal conductivity = 1.

c = heat capacity = 1.

a = thermal diffusivity = k/pc = 1.

V = velocity = 1.

m = mass flow rate = r*A*v = $7.85*10^{-5}$

Boundary conditions

h = convection coefficient = 0.005

T_0 = pipe wall temperature = 0.

T_1 = inlet (x=0.) temperature = 2.

T_2 = exit (x=2l) temperature = 1.

Workshop problem: Advection – Diffusion

Carslaw & Yaeger, Conduction of Heat in Solids, 2nd ed., p148

$$T = \frac{T_2 e^{-V(L-x)/2\alpha} \sinh \xi x + T_1 e^{Vx/2\alpha} \sinh \xi (L-x)}{\sinh \xi L}$$

$$\xi = \sqrt{\frac{V^2}{4\alpha^2} + \frac{hp}{Ak}}$$

$$\alpha = \frac{k}{\rho c}$$

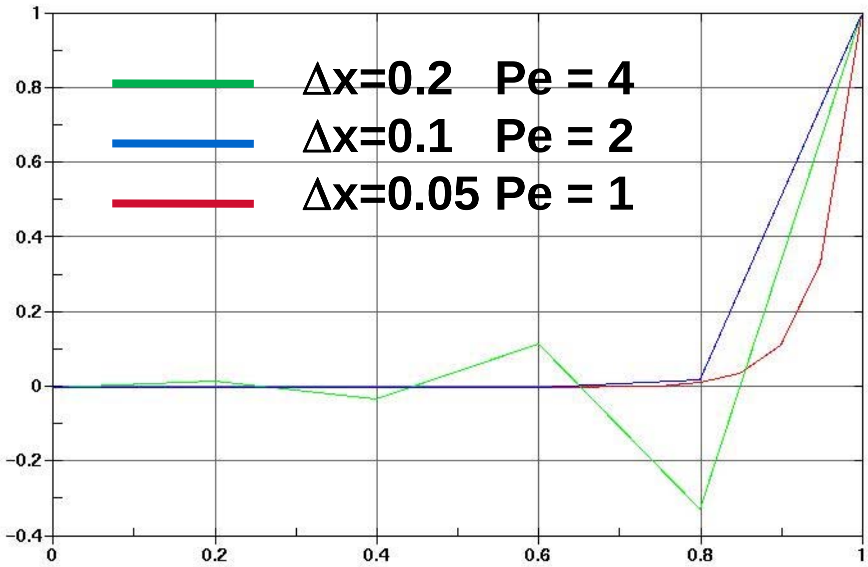
Three analytical solutions to benchmark against: T at x = 0.5	
1) pure conduction	**T = 1.500**
2) conduction + advection (h=0)	**T = 1.622**
3) conduction + advection + convection	**T = 1.293**

BOUNDARY_THERMAL_BULKFLOW_UPWIND

Advanced feature

LSTC

For many flow problems, dissipative mechanisms are only significant in a narrow layer typically adjacent to a boundary. Computational solutions obtained with grids appropriate to the main flow region are often oscillatory when the true solution changes rapidly across the boundary layer.



1D steady advection diffusion problem

$$V\frac{dT}{dx}-\alpha\frac{d^2T}{dx^2}=0$$

with T(0)=0. and T(1)=1.

'Wiggles' occur at cell Peclet numbers greater than 1.

$$Pe=\mathrm{Re}\,\mathrm{Pr}=\left(\frac{\rho V\Delta x}{\mu}\right)\left(\frac{\mu c}{k}\right)=\frac{V\Delta x}{\alpha}$$

C.A.J. Fletcher, Computational techniques for Fluid Dynamics 1, Springer Verlag, 2nd ed., p293.

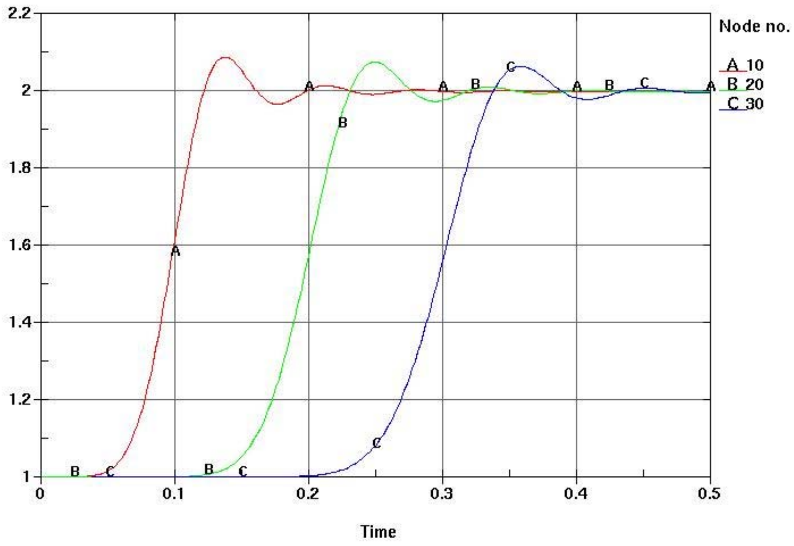
BOUNDARY_THERMAL_BULKFLOW_UPWIND

Advanced feature, upwind_transient.k

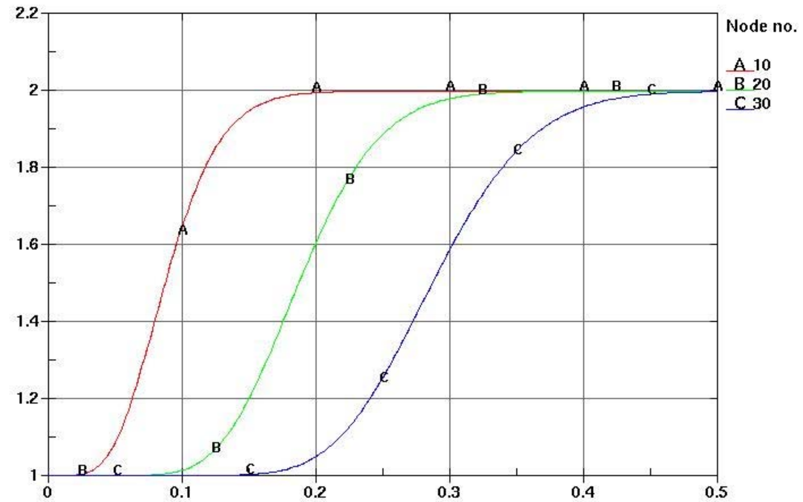
LSTC

UPWIND adds a term (sometimes called artificial viscosity) to the element stiffness matrix. This eliminates the 'wiggles' but also makes the solution more diffusive. Note that the curves are now not as steep and their shape is more spread out over time. Wiggles are gone but the solution is less accurate.

UPWIND off



UPWIND on

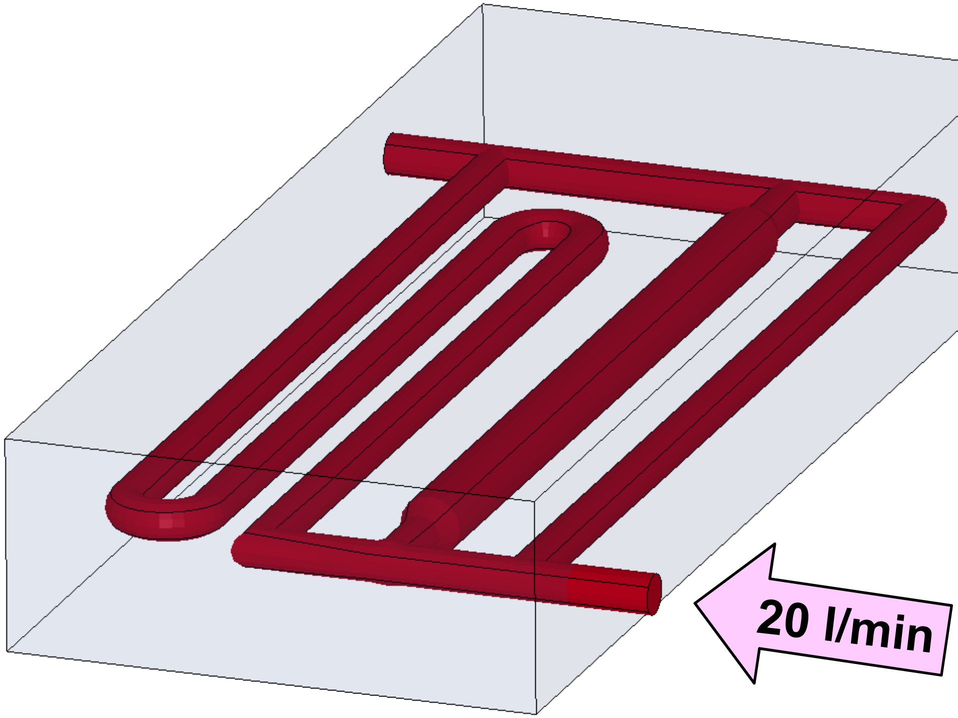


Transient 1D flow with a step change in entering fluid temperature. Shown is the temperature history at 3 locations down the pipe. Initial and boundary conditions: T(x,0)=1, T(0,t)=2.

Pipe Network

Think about pipes in your house. The starting point is the valve on the pipe entering your house. We will call this NODE 1. Node 1 is special and has a boundary condition specified. The BC is the pressure you would read on a pressure gauge at this location. The water enters your house and passes through several pipe junctions before it exits through your garden hose. Every junction is represented by a NODE. The last node also needs a BC specified. This BC is the mass flow rate. The pipe flow code will calculate the pressure at the intermediate junction nodes and the flow rate through the pipes.

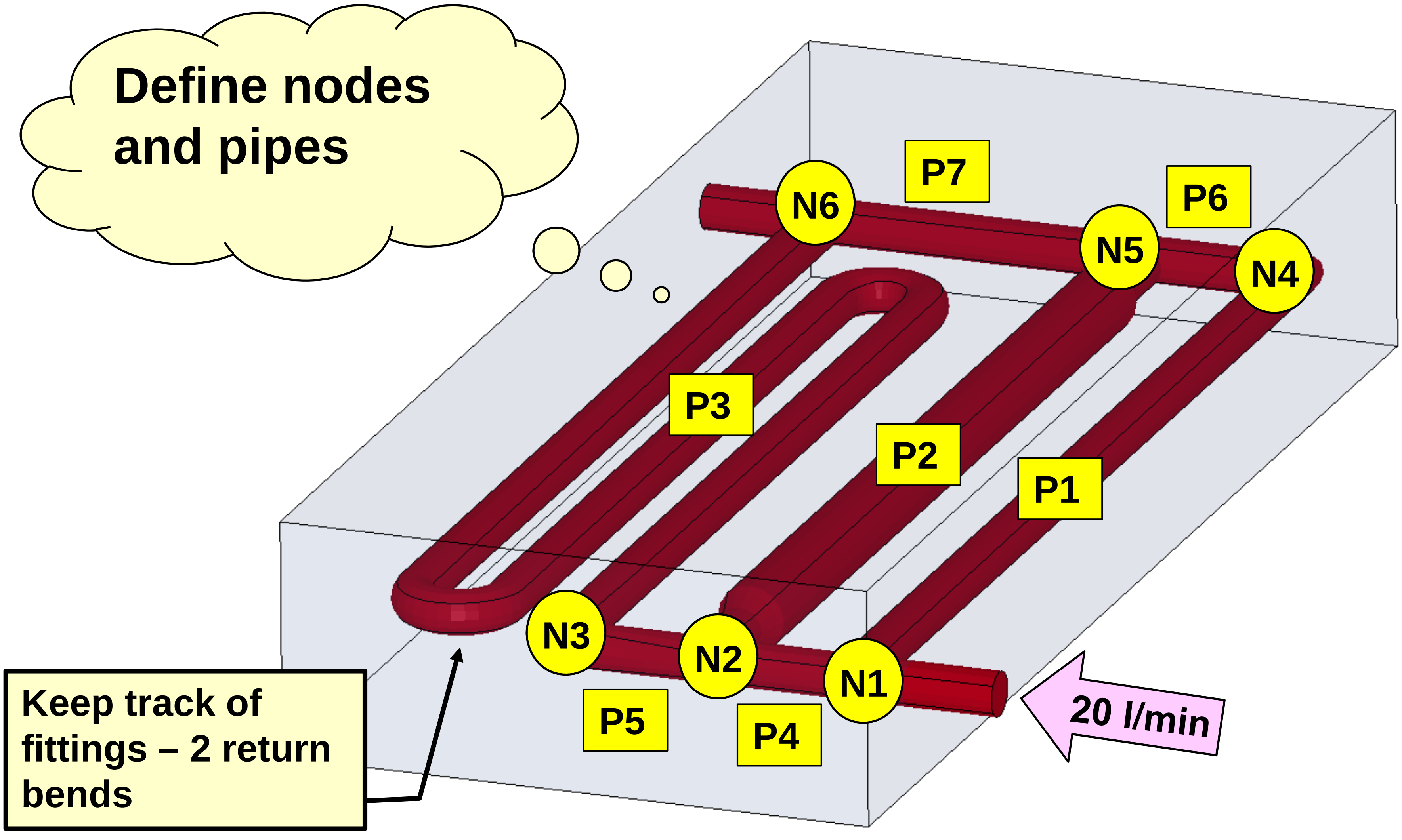
Pipe Network



Given an entering flow rate, calculate the flow in each pipe and the convection heat transfer coefficient

Pipe Network

Define nodes and pipes



Pipe Network

LSTC

input | output

Pipe	N1	N2	Length [m]	Dia. [mm]	Rough [mm]	Ftg. [L_e/D]	Q [l/min]	h [W/m²C]
1	1	4	1	10	0.05		5.7	5600
2	2	5	1	20	0.05		9.7	2400
3	3	6	3	10	0.05	100	4.5	4600
4	1	2	0.2	10	0.05		14.2	11000
5	2	3	0.2	10	0.05		4.5	4600
6	4	5	0.2	10	0.05		5.7	5600
7	5	6	0.4	10	0.05		15.5	12000

Pipe Network

Pipe type	Roughness, e [mm]
Cast iron	0.25
Galvanized iron	0.15
Steel or wrought iron	0.046
Drawn tubing	0.0015

Fitting type	Equivalent length L_e/D
Globe valve	350
Gate valve	13
Check valve	30
90º std. elbow	30
90º long radius	20
90º street elbow	50
45º elbow	16
Tee flow through run	20
Tee flow through branch	60
Return bend	50

Pipe Network

Solution algorithm

Solve:

Bernoulli equation

$$\left(\frac{V_1^2 - V_2^2}{2g}\right) + \left(\frac{P_1 - P_2}{\rho g}\right) + (z_1 - z_2) = H_f$$

Friction equation

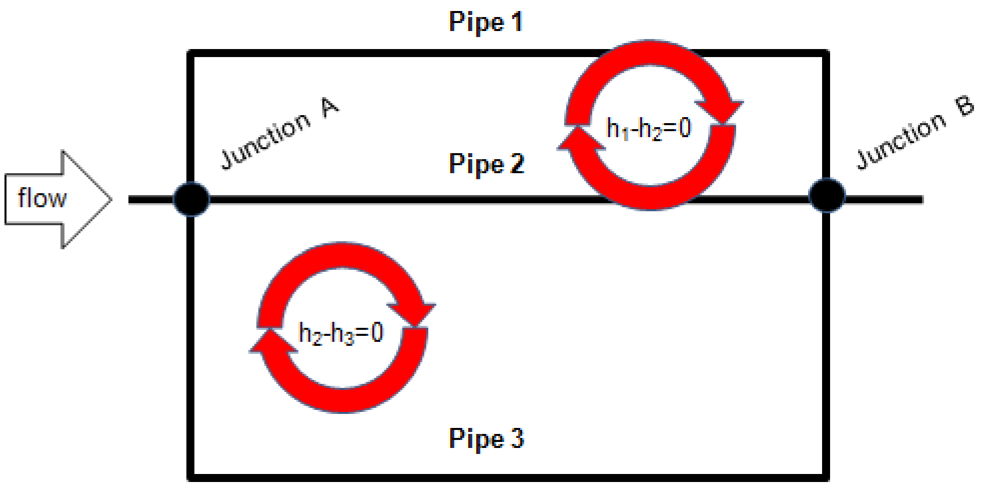
$$H_f = f\frac{L}{D}\frac{V^2}{2g} + H_{fitting}$$

Gnielinski equation

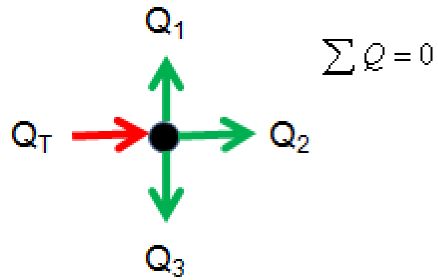
$$h = \left(\frac{k}{D}\right)\left[\frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7(f/8)^{0.5}\left(\mathrm{Pr}^{2/3} - 1\right)}\right]$$

Subject to:

Pressure drop around each circuit =0.

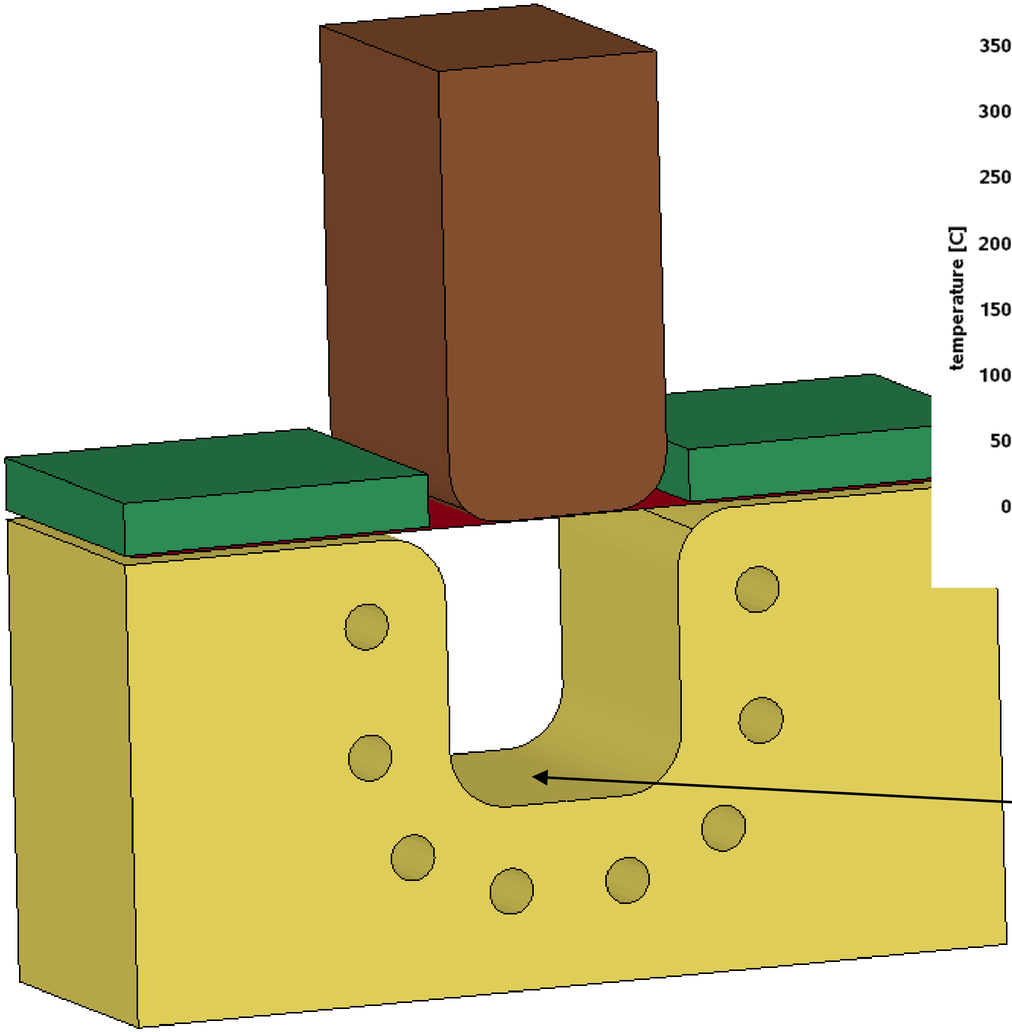


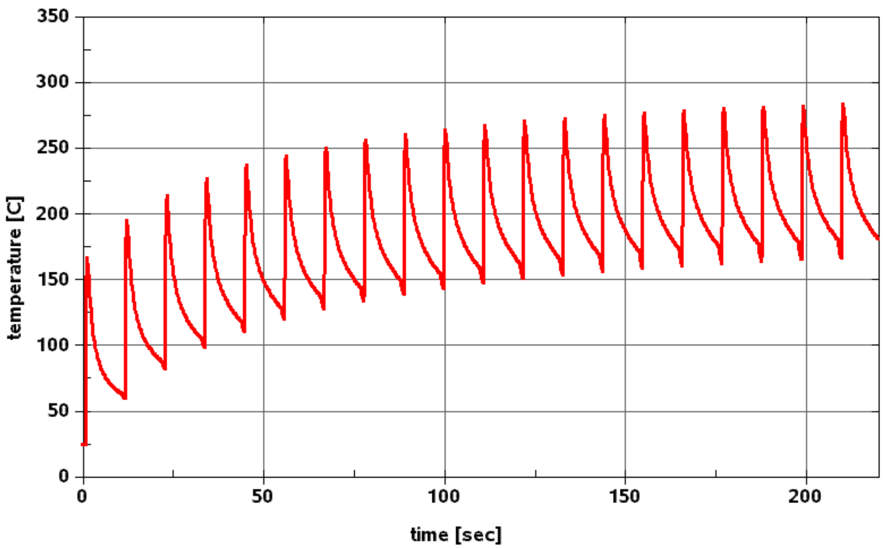
Flow into each junction = 0.



Process start-up time

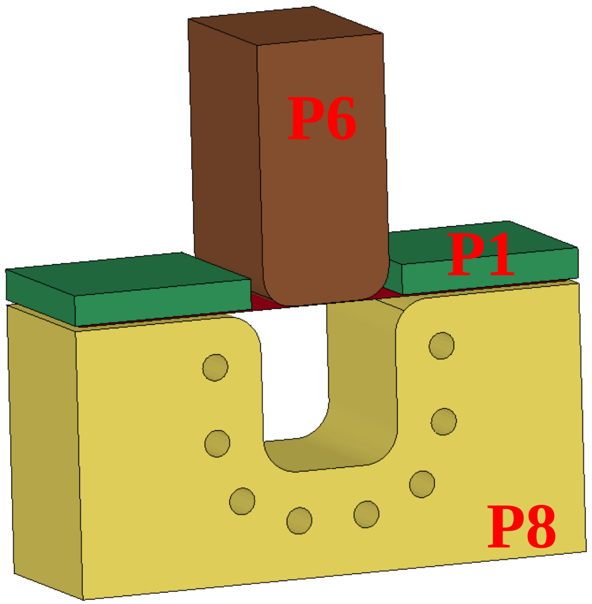
LSTC





Shown is the tempeature history for this location during 20 stamping cycles.

Process start-up time



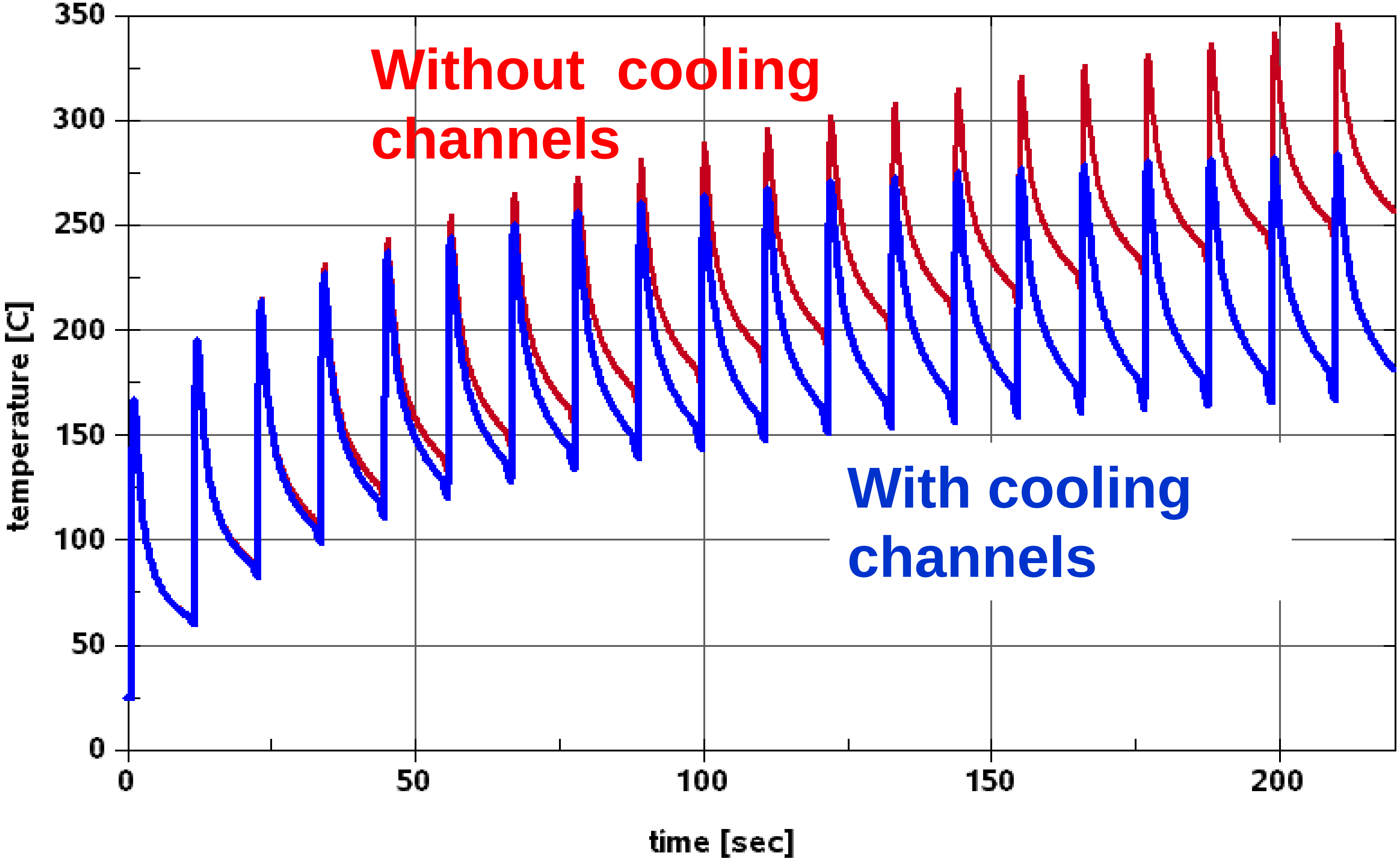

```
*KEYWORD
*INITIAL_TEMPERATURE_SET
$     nsid      temp
         1        25.
         6        25.
         8        25.
*END
```

```
*INCLUDE

new_temp_ic.inc

*INTERFACE_SPRINGBACK_LSDYNA
$     psid
         1
*SET_PART_LIST
$     psid
         1
$     pid1     pid2     pid3
         1        6        8
```

```
#!/bin/csh -f
set i=1
while ( $i <= 20 )
./ls971 i=stamping.k g=d3plot$i"_"
@ i = $i + 1
end
```

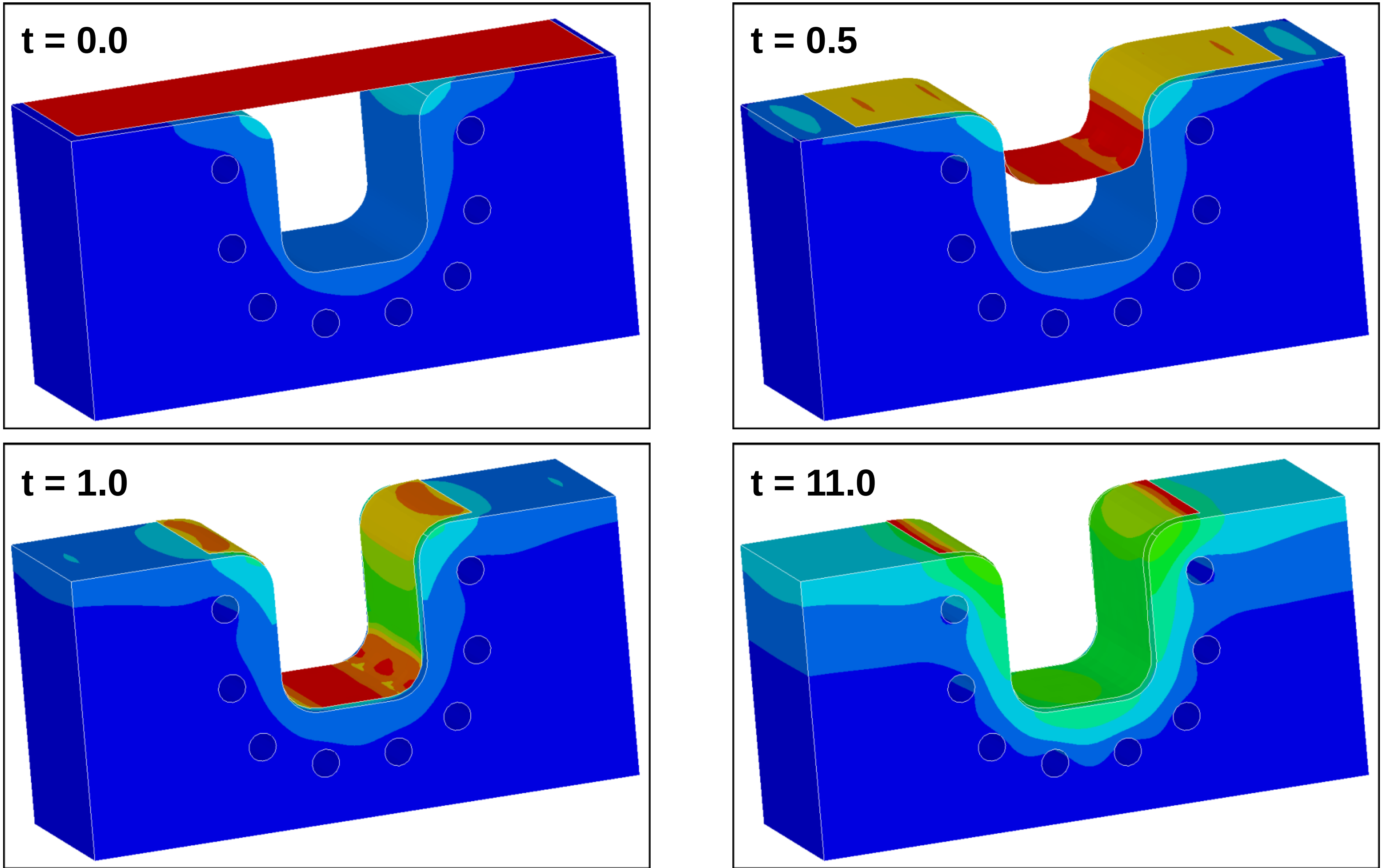
Process start-up time

Tool temperature after 20 stampings



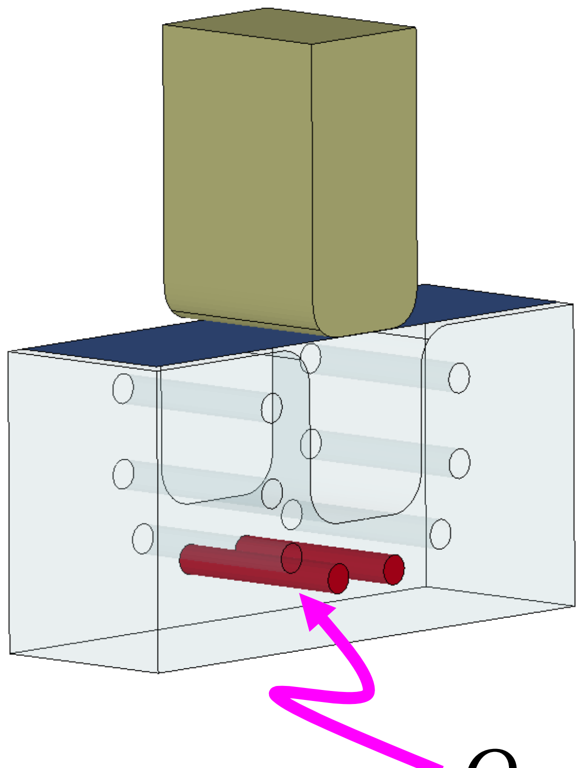
Process start-up time

LSTC



Thermostat feature adjusts the heating rate to keep the sensor temperature at the set point.

LSTC



***LOAD_HEAT_CONTROLLER**

Q_{cont}	volumetric heating rate
Q_0	constant volumetric heating rate
G_p	proportional gain
G_i	integral gain
T_{set}	set point temperature
T	sensor temperature (at a node)

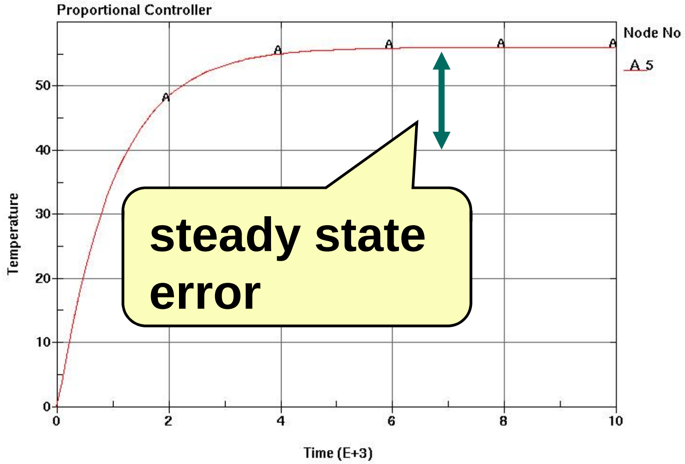
$$Q_{cont} = Q_0 + \underbrace{G_p\left(T_{set} - T\right)}_{\text{proportional}} + \underbrace{G_i \int_{t=0}^{t} \left(T_{set} - T\right) dt}_{\text{integral}}$$

proportional

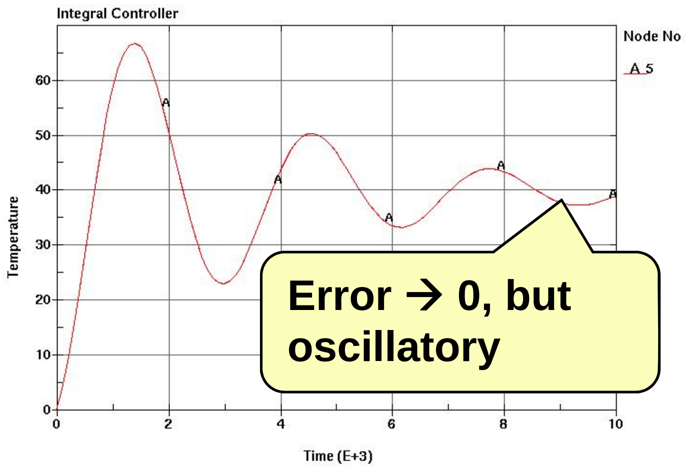
integral

Thermostat controller

set point T_{set}=40



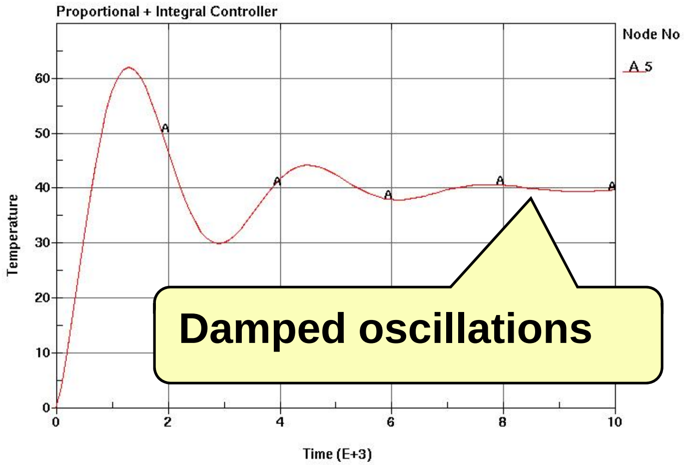
Proportional Control – corrective action is taken which is proportional to the error. Should a sustained correction (brought about by a sustained disturbance) be required, an accompanying steady state error will exist.



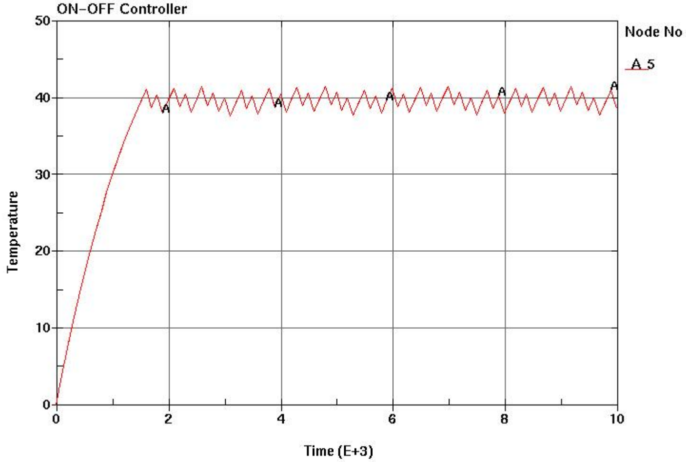
Integral Control – corrective action is made which is proportional to the time integral of the error. An integral controller will continue to correct until the error is zero (eliminating any steady state system error). But, there is also a weakness. Integral control tends to overshoot, thereby producing an oscillatory response and, in some cases, instability.

Thermostat controller

Set point T_{set}=40



Proportional + Integral Control – the oscillations will be damped and the set point error → 0.



On – Off Control can also be activated.

Thermostat controller

*LOAD_HEAT_CONTROLLER keyword

LSTC

NODE	PID	LOAD	TSET	TYPE	GP	GI

NODE	sensor is located at this node
PID	heater (or cooler) part id being controlled
LOAD	heater output Q_0 [W/m^3]
TSET	set point temperature @ NODE
TYPE	1 = on off 2 = proportional + integral
GP	proportional gain
GI	integral gain