Heat Transfer in LS-DYNA

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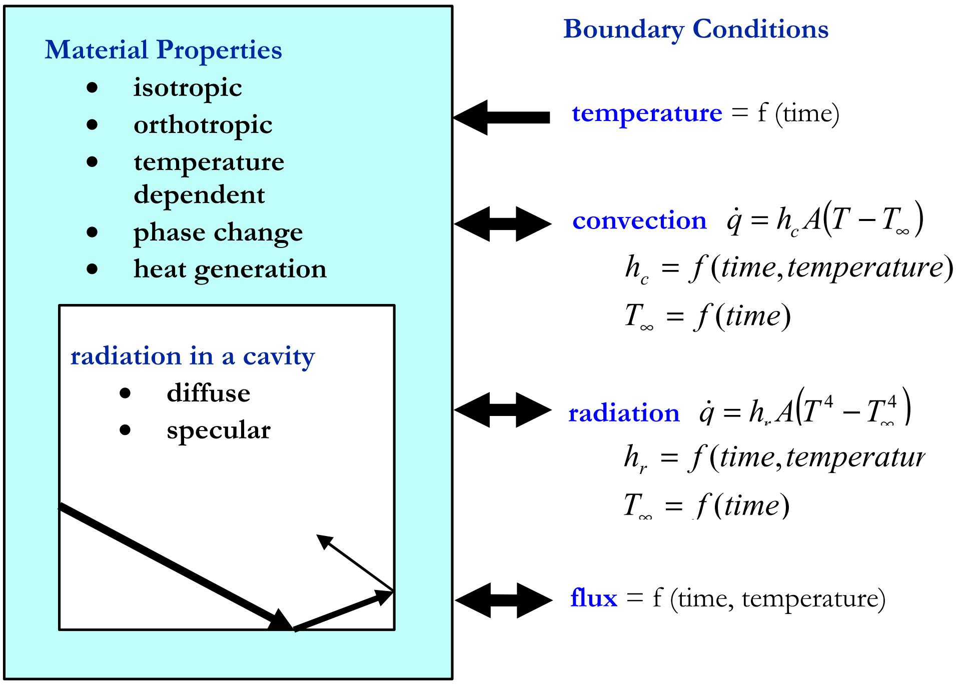
ABSTRACT

LS-Dyna can solve steady state and transient heat transfer problems on 2-dimensional parts, cylindrical symmetric parts (axisymmetric), and 3-dimensional parts. Heat transfer can be coupled with other features in LS-DYNA to provide modeling capabilities for thermal-stress and thermal-fluid coupling. This paper presents several examples using LS-DYNA for modeling manufacturing processes (e.g., upseting, extrusion, welding, casting).

HOW TO USE LS-DYNA FOR HEAT TRANSFER

Heat transfer modeling options in LS-DYNA are summarized in the following figure.



Boundary conditions include temperature, flux, convection, and radiation. Material properties can be isotropic or orthotropic. Thermal conductivity and heat capacity can be functions of temperature. The material can undergo solid-liquid phase change and be defined with a heat generation rate that can be a function of time and temperature. Enclosure radiation heat transfer can be modeled using diffuse or specular surfaces.

Other features are described in the boxes below:

Element Types

- 8 node brick & 4 node quad
- 4 node shell (membrane)
- 12 node quadratic shell

Element Integration

- 1 point quadrature => best for coupled thermal-stress problems
- 8 point quadrature => best for thermal only problems

Analysis Type

- steady state
- transient
  - fully implicit scheme
  - Crank Nicolson scheme

Equation Solver

- direct (Gauss) solver
- conjugate gradient iterative
  - diagonal scaled preconditioned
  - incomplete Choleski

The box below shows the minimum number of keywords required for a thermal analysis. Other keywords are available to define initial conditions, boundary conditions, slide surfaces, heat generation, material properties, and special features (e.g., weld heat source, thermostat). The LS-Dyna Keyword User Manual should be consulted for a description of these keywords.

```
*CONTROL_SOLUTION
         1
*CONTROL_THERMAL_SOLVER
         1
*CONTROL_THERMAL_TIMESTEP
         0         1.        .1
*DATABASE_TPRINT
        .1
*PART
aluminum block
         1         1         1
*MAT_THERMAL_ISOTROPIC
         1      2700.         0  2.44e+07
      904.      222.
```

0 = mechanical
1 = thermal
2 = mech + therm

1 Gauss solver
2 iterative solver

thermal material number flag

In a coupled thermal-stress analysis, the thermal time step is independent from the mechanical time step. Use the keyword *CONTROL_THERMAL_TIMESTEP to set the value. For most problems, the implicit thermal time step is chosen equal to the implicit mechanical time step, or 10 to 100 times greater than the explicit mechanical time step. The rate of mechanical motion, mechanical deformation, and rate of heat transfer must all be considered in selecting an appropriate time step. The thermal-stress calculation procedure is as follows:

Mechanical Calculations
Based on current temperature, calculate:

- **plastic work**
- **part contact gap thickness**
- **temperature dependent material properties**
- **thermal expansion**
- **update geometry**

⟷

Thermal Calculations
Based on current geometry, calculate:

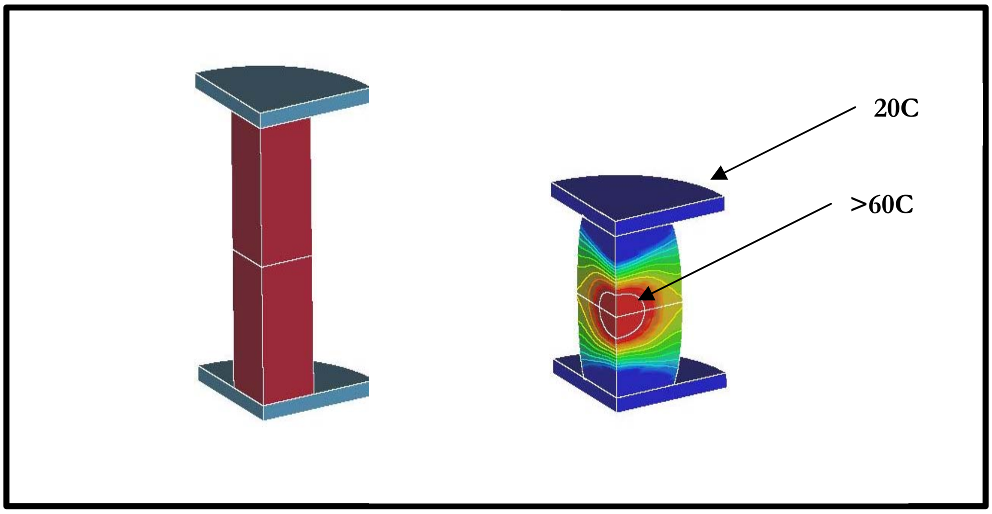
- **heat from plastic work**
- **contact conductance based on gap thickness**
- **heat from interface friction**
- **update temperature**

The following mechanical constitutive models have the thermal coefficient of expansion in their definition:

- Type 4 *MAT_ELASTIC_PLASTIC_THERMAL
- Type 21 *MAT_ORTHOTROPIC_THERMAL
- Type 106 *MAT_ELASTIC_VISCOPLASTIC_THERMAL

UPSET PROBLEM

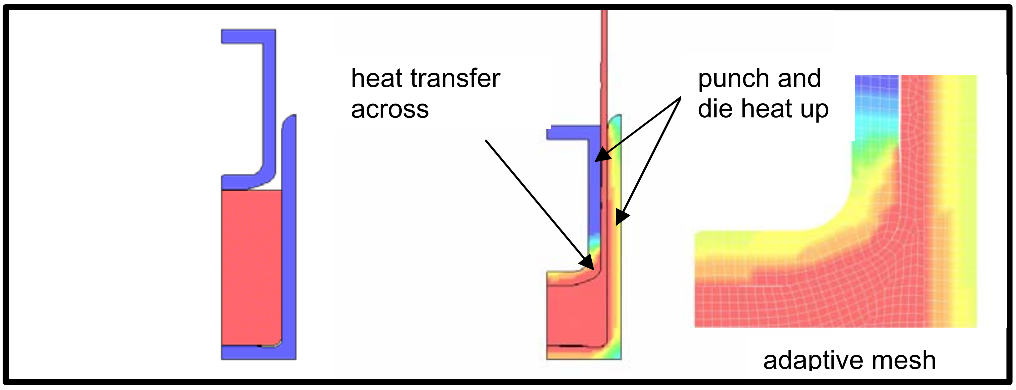
In metal forming processes such as rolling, extrusion, and stamping, large plastic deformation of the metal occurs. The temperature of the body changes due to the conversion of mechanical work into heat through plastic deformation. The upsetting process is defined as the axial compression of a cylinder between two perfectly rough, insulated plates. The process is fast enough such that there is no heat transfer with the environment.



The upsetting problem shown in the box above is described in detail in a publication by J. van der Lugt [2]. The low carbon steel sample has an initial height of 36 mm, radius of 9 mm, and initial temperature of 20 C. The total compression is 44% (i.e., ? h/h) in 1.6 seconds. Note that the top and bottom surfaces of the cylindrical specimen are constrained in the radial direction. The temperature increase of the cylinder is completely due to the conversion of plastic work to heat.

BACK EXTRUSION FORGING

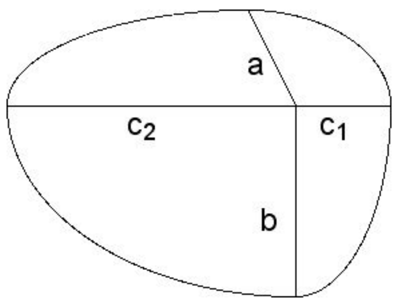
The back extrusion problem shown in the box below is hypothetical. It is used as a validation problem for several features in LS-DYNA (e.g., adaptive meshing, thermal-mechanical slide surfaces). The initial position of the punch is shown in the figure on the left. The punch and die are at room temperature (shown in blue), while the work-piece is hot (shown in red).



The hot work-piece is back extruded through the gap between the cold punch and die. Note the heat transfer across the contact surfaces. Also, note the thermal-mechanical adaptive mesh refinement in the extruded part.

WELDING

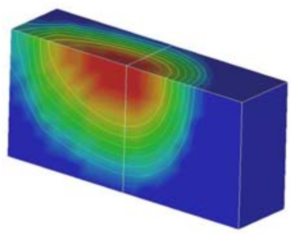
The problems of distortion, residual stresses, and reduced strength of a structure in and around a welded joint are a major concern of the welding industry. The interaction of a heat source (e.g., arc, electron beam, laser) with a weld pool is a complex physical phenomenon that still cannot be modeled rigorously. LS-DYNA uses a weld heat source model developed by J. Goldak [3] to model the weld heat source. The Goldak weld heat source model is based on a Gaussian distribution of power density in space. A feature of the model is that a double ellipsoidal energy deposition profile is used so that the size and shape of the heat source can be easily changed to model both the shallow penetration arc welding process and the deeper penetration laser and electron beam processes. The model is described by the equations in the box below.



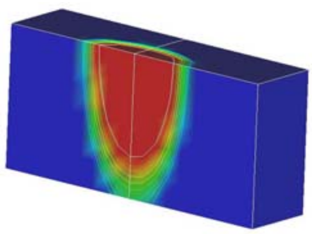
$$\dot{q}_f''' = \frac{6\sqrt{3}F_f Q}{abc_1\pi\sqrt{\pi}} e^{-\frac{3x^2}{a^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3(z+vt)^2}{c_1^2}}$$

$$\dot{q}_r''' = \frac{6\sqrt{3}F_r Q}{abc_2\pi\sqrt{\pi}} e^{-\frac{3x^2}{a^2}} e^{-\frac{3y^2}{b^2}} e^{-\frac{3(z+vt)^2}{c_2^2}}$$

The weld heat source is described by a power density Q [W/m^3] and a velocity, *v,* across the surface. The double ellipsoidal approach is represented by a leading edge distribution, $\dot{q}_f'''$, and a trailing distribution, $\dot{q}_r'''$. The energy deposited in the front and rear quadrants are defined by the fractions F_f and F_r. The weld shape parameters (a, b, c_1, c_2) are given in Goldak's paper for several welding types. These parameters are defined using the *BOUNDARY_THERMAL_WELD keyword in the input file. An example of an arc and an electron beam weld are shown in the box below.



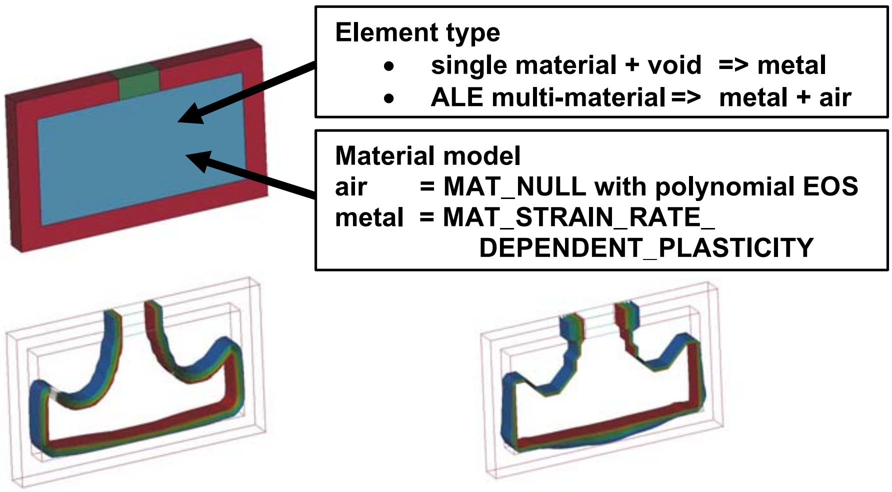
TIG a=1, b=2, c_1=1, c_2=4



Laser a=1, b=5, c_1=1, c_2=1

CASTING

This hypothetical plate casting problem demonstrates features in LS-DYNA to model filling a mold with liquid metal and heat transfer during solidification and cool down to room temperature. The mold is modeled as a Lagrangian solid. The volume within the mold can be modeled in two ways: (1) as a single material Euler element plus void which models metal filling a cavity under vacuum; or (2) multi-material ALE element which models metal filling a cavity initially filled with air. The element formulation parameter (ELFORM) on the *SECTION_SOLID keyword card is used to distinguish between these two options. An equation of state is used to model the fluid behavior of the liquid metal. Material model MAT_STRAIN_RATE_DEPENDENT_PLASTICIY can also be used to model a liquid metal. Liquid metal inflow is specified by the ambient element type (AET) parameter on the *SECTION_SOLID keyword card. The ambient element nodes are given a velocity boundary condition to model the inflow velocity of metal into the mold. The following figure shows the metal flow front (void fraction) at an instant in time during the fill process. Also shown are temperature contours. Note the heat transfer from the hot metal to the colder mold at the mold bottom.



void fraction temperature

CONCLUSION

Four coupled thermal-mechanical examples were presented in this paper demonstrating the capabilities of LS-DYNA in modeling industrial processes. New features under development include:

1. A 12 node thermal quadratic shell element for sheet metal forming problems where prediction of temperature through the thickness of the shell and its affect on mechanical properties is important.

2. Frictional heating due to sliding on contact surfaces.

3. Enclosure radiation modeling of specular surfaces by Monte Carlo radiation transport calculations.

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