

Using LS-DYNA for Hot Forming

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Summary:

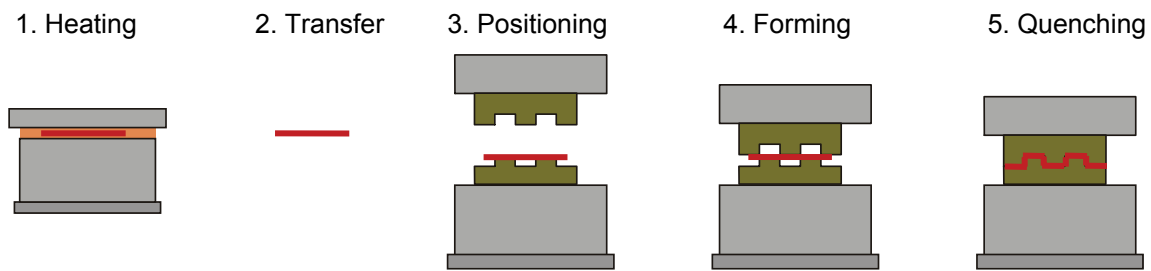
LS-971 has several features to model the hot forming process. A thick thermal shell formulation for the blank allows modeling a temperature gradient through the thickness. The keyword, *MAT_ADD_THERMAL_EXPANSION, allows calculating thermal strains for all the mechanical material models. A user defined flag is available to turn off thermal boundary conditions when part surfaces come in contact. A thermal one-way contact algorithm is available to more accurately calculate contact between a die zoned with a CAD type surface mesh when in contact with a uniform meshed blank. Thermal-mechanical contact user defined parameters allow modeling the coefficients of friction as a function of temperature and thermal contact resistance as a function of interface pressure. A new feature models bulk fluid flow through the die cooling passages.

Keywords:

hot stamping, metal forming, heat transfer, thermal stress

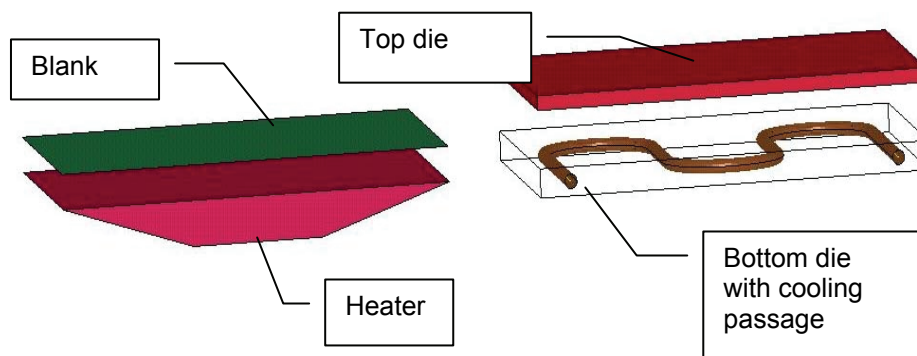
1 Introduction

This paper presents features in LS-DYNA useful in modelling hot forming. The hot forming process has 5 steps [1]:



1. Heating → The blank is heated and held at the austenization temperature of 950C.
2. Transfer → The blank cools by convection and radiation during transfer from the oven to the forming press.
3. Positioning → The blank is placed on the lower die and begins to cool due to contact with the colder die.
4. Forming → The blank is formed.
5. Quenching → The blank is held in the press and cooled to induce a solid-solid phase transition from austenite to martensite.

The finite element model is shown below.



2 Heating to the Austenization Temperature

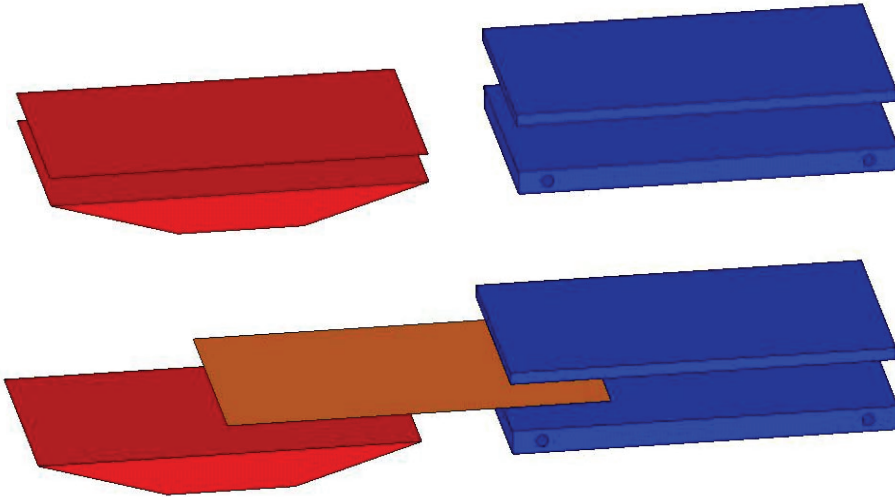
The first step is to heat the blank from room temperature (~25C) to the austenization temperature (~950C) as shown in the computational sequence below.



This figure shows the blank increasing in temperature from 25C to 450C to 950C. The red trapezoidal shaped part represents the furnace at 1100C. The easiest modeling technique is to define the initial temperature condition of the blank to be 950C. However, if the time required to heat the blank is desired, then a boundary condition must be defined. LS-DYNA allows flux, convection, and radiation boundary conditions. The blank in this model is heated by convection. The convection heat transfer coefficient is enhanced to include radiation heat transfer affects. This is a technique that will linearize the problem and decrease CPU time. An option is to model the radiation transport within the heating oven using the keyword `*BOUNDARY_RADIATION_SET_VF_CALCULATE`. This keyword will activate the calculation of radiation view factors and perform grey body radiation transport between the blank and oven heating zones.

3 Transfer from Oven to Forming Press

The second step is to transfer the hot blank from the oven or heating zone to the dies as shown in the computational sequence below. The blank loses heat by convection heat transfer to the environment at 25C. In this model, the blank cools by 50C during the transfer operation.



The value chosen for the convection heat transfer coefficient is the most important parameter for this part of the calculation. The convection coefficient can be entered as a constant, as a function of temperature defined by a data curve, or using the new keyword `*DEFINE_FUNCTION`. `DEFINE_FUNCTION` allows you to enter an equation using FORTRAN or C syntax in the input file. This allows the calculation of convection coefficients using standard empirical equations from the literature such as:

$$\text{Blank top surface} \quad h_{top} = [0.14(Gr * Pr)^{0.25}] \frac{k}{l}$$

$$\text{Blank bottom surface} \quad h_{bot} = [0.27(Gr * Pr)^{0.25}] \frac{k}{l}$$

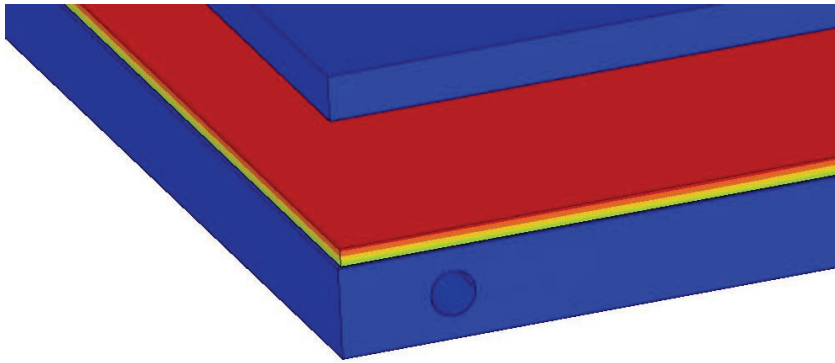
The following text box shows an example in the use of this keyword. The function ID number (FIDH) is referenced on the `*BOUNDARY_CONVECTION` keyword and then defined using the `*DEFINE_FUNCTION` keyword.

```
*BOUNDARY_CONVECTION_SEGMENT
$   LCIDH      HM      LCIDT      TM      LOC      FIDH      FIDT
      0        0.      0          10.     0         4         0
*DEFINE_FUNCTION
  4
h(x,y,z,vx,vy,vz,temp,tinf,time) = 0.27 * (Gr * Pr)**0.25 * k/l
```

The value for the Grashof number (Gr) and the Prandtl number (Pr) can be entered as parameters or they can also be expanded inline by defining them as functions.

4 Positioning

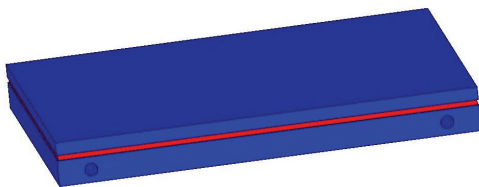
The blank is placed on the lower die and begins to cool due to contact with the colder die as shown in the following figure. The attribute flag "thickness on" is enabled in LS-PrePost so that blank thickness can be displayed. An important modelling technique is to turn any thermal boundary condition off when the surface of the blank comes in contact with the die. This is accomplished by setting a flag (BC_FLAG) on the `*CONTACT_THERMAL` keyword.



Note the temperature gradient through the thickness of the blank. The blank is modelled by a thin mechanical shell and flagged to be treated as a thick thermal shell by the parameter TSHELL on the *CONTROL_SHELL keyword. The thick thermal shell is a 12 node element – 4 nodes in the plane of the shell and 3 nodes through the thickness. The 3 nodes through the thickness allow the use of quadratic shape functions to more accurately calculate the through thickness temperature gradient.

5 Forming

The forming operation is depicted in the following figure. In the plant, the forming operation completes in a fraction of a second, but requires several hours of CPU time on MPP computers to simulate.



Nothing of interest happens in this hypothetical simulation since the die surfaces are flat. However, in a real simulation, the answers drive the design of the dies and the manufacturing process parameters. LS-DYNA has several features useful in modelling the forming process.

***MAT_ADD_THERMAL_EXPANSION** - The coefficient of thermal expansion as a function of temperature can be defined using this keyword. This allows the calculation of thermal strains for any of the mechanical material models in LS-DYNA.

***CONTACT_(option)_THERMAL_FRICTION** - The suffix FRICTION enables the capability to model the mechanical coefficients of friction as a function of temperature and the thermal contact resistance as a function of interface pressure. There are currently 4 formulas to calculate the contact resistance, h , as a function of interface pressure, P :

load curve $h(P)$ is defined by a load curve

polynomial $h(p) = a + bP + cP^2 + dP^3$

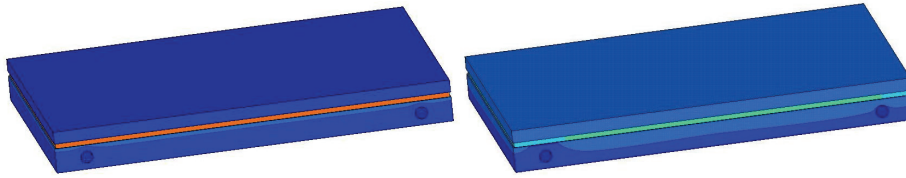
Shvets formula [2]
$$h(P) = \frac{\pi k_{gas}}{4\lambda} \left[1 + 85 \left(\frac{P}{\sigma} \right)^{0.8} \right]$$

Sellers formula [3]
$$h(P) = a \left[1 - \exp\left(-b \frac{P}{c}\right) \right]^d$$

Additionally, a user subroutine allows the creation of other models.

6 Quenching

The quenching process, which lasts for 10 to 30 seconds, is shown in the computational sequence below. Notice that the blank cools down from the left figure to the right figure and the dies increase



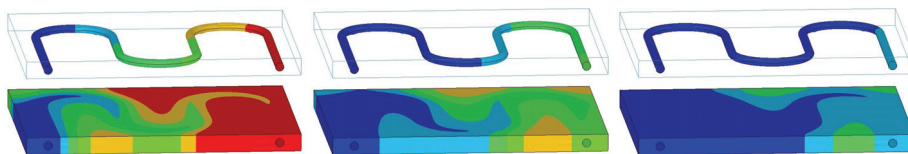
in temperature. The cooling rate of the blank affects the hardening properties of the material. Material type 113 features a special hardening law [4] aimed at modelling the temperature dependent hardening behaviour of TRIP-steels. TRIP stands for Transformation Induced Plasticity. The material gains ultra high strength through the hot forming process. In this material, a phase transformation from austenite to martensite occurs during forming, an effect which is sensitive not only to the strain level, but also to strain rate and temperature. The material model is composed of 2 basic equations:

1. TRIP kinetics rate equation
$$\frac{\partial V_m}{\partial \varepsilon} = \frac{B}{A} \exp\left(\frac{Q}{T}\right) \left(\frac{1-V_m}{V_m}\right)^{(1+B)/B} V_m^P \frac{1}{2} (1 - \tanh(C + DT))$$
2. yield stress equation
$$\sigma_y = \{B_{HS} - (B_{HS} - A_{HS}) \exp(-m\varepsilon^n)\} (K_1 + K_2 T) + \Delta H_{\gamma \rightarrow \alpha} V_m$$

Additionally, a user subroutine is available that allows the creation of more sophisticated material models with the interchange of material history variables between the mechanical material user subroutine and the thermal material user subroutine.

7 Die Cooling

Although not previously mentioned as a process step, the dies must be cooled during the quenching process. Also, the dies must be cooled to some operating temperature before the next hot blank can be formed. The computational sequence below shows fluid entering the lower die cooling passage at 25C. As the fluid passes through the die it increases in temperature as it absorbs heat from the hotter die. The die in turn decreases in temperature as shown in the following figure.



Cooling passage fluid flow is defined by beam elements that trace the centreline of the passage through the die. The keyword *BOUNDARY_THERMAL_BULKFLOW assigns a mass flow rate to the beam. The beam formulation is unique in that it includes the advection terms to model fluid flow. The assumption is that the flow is turbulent and therefore well mixed. Additionally, the flow is inviscid. These are typical assumptions made in designing heat exchangers.

Each beam is wrapped with a thin walled cylinder made of shell elements. The radius of the cylinder is the radius of the pipe. This cylinder can be thought of as the outer surface of the fluid. The keyword *BOUNDARY_THERMAL_BUKNODE associates nodes on the beam with the surrounding shells. This keyword also includes the heat transfer parameters to model the fluid-structure interaction.

8 Summary

This paper presents LS-DYNA input keywords essential to modeling the Hot Forming process. Example input files can be obtained by contacting the author at shapiro@lstc.com.

9 Literature

1. Courtesy of David Lorenz, Mercedes Car Group, Germany.
2. I.T. Shvets, "Contact Heat Transfer Between Plane Metal Surfaces", Int. Chem. Eng., Vol. 4, No. 4, p621, 1964.
3. Li & Sellers, Proc. Of 2nd Int. Conf. Modeling of Metals Rolling Processes, The Institute of Materials, London, 1996.
4. D. Hilding & E. Schedin, "Experience from Using a New Material Model for Stainless Steels with TRIP-effect", 5th European LS_DYNA Users Conference, Birmingham, UK, 2005.