Recent Advances and New Developments in
Hot Forming Simulation with LS-DYNA

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Abstract:

The analysis and optimization of hotforming processes necessitates the use of thermal-mechanical coupled finite element simulations. One of the key issues in process simulation is the choice of an appropriate modelling approach for the tools. Splitting the process into the two fundamental partial stages forming and cooling is an efficient way to set up a simulation model. The forming stage needs the tool surface discretized with a rather fine shell mesh to meet typical geometric accuracy requirements. The quenching stage furthermore requires a 3-dimensional volume mesh to account for the heat dissipation into the tools. Model size and meshing effort both can be considerably reduced if the volume mesh is generated independently of the geometric accuracy requirements for the surface representation. Thermal contact options in LS-DYNA are then used to connect the fine surface shell mesh and the volume mesh to enable an accurate prediction of the contact situation and moreover the calculations of the 3-dimensional heat flow into the tool. A recent development is a simplified 1D-fluid flow calculation in the thermal solver to consider cooling passages in the tools. This feature enables thermal tool analysis after a sequence of several production cycles.

Keywords:

hotforming, thermal-mechanical coupling, process modeling, thermal analysis

1   Introduction

Within the current political debate on climate protection lightweight design gains more importance in the automotive industry. Hotforming and quenching of heat-treatable steels is an effective way to improve the component strength of structural parts and thereby reduce the weight of the car body. In contrast to conventional sheet metal forming simulations the analysis and optimization of hotforming processes necessitates the use of thermal-mechanical coupled finite element simulations. The thermal-mechanical coupling is necessary to consider the fast cooling taking place in areas where the hot blank comes into contact with the colder die. This local cooling effects lead to high temperature gradients and an inhomogeneous temperature distribution in the blank during the forming operation. Since the actual temperature has a strong impact on the mechanical material properties e.g. the yield stress an accurate calculation of the current temperature field during the forming operation is a basic prerequisite for an accurate calculation of the plastic deformation of the material. Once the tool has reached the bottom dead centre and the forming operation is finished the quenching of the hotformed component takes place. Successful quenching of the final part can be verified within a cooling simulation. For several reasons it is not efficient to perform the analysis of the forming operation and the quenching in one and the same simulation step. This is discussed in detail in the following chapters. If the thermal behaviour of the tool during a sequence of production cycles should be investigated the cooling system has to be considered in the simulation.

2   Process Modelling Approach

Modelling a complete hotforming process one has to consider multiple partial problems. The feasibility of the forming operation is therein only one partial problem, which is focussed in the beginning of a process optimization. An efficient modelling approach has to be adapted to the typical workflow of a process and die designer as shown in figure 1 below. The first step is the feasibility study of the part geometry. Major design criteria in this process planning phase are the maximum allowed thickness reduction inside the part trimline and the formation of wrinkles during the forming operation. If the feasibility of the desired part geometry can be ensured by means of a forming simulation, the cooling of the formed part in the closed tool moves into the centre stage of the analysis. One major design criterion in this phase is the minimum holding time in the closed tool, where the part is cooled down rapidly below the martensite finish temperature Mf to ensure successive hardening. A reduction of the holding time has a direct impact on the economic efficiency of the process. Considering this effect requires a more detailed modelling approach for the tools to account for the heat conduction inside the tools and the heat transfer from the tools into the cooling system.
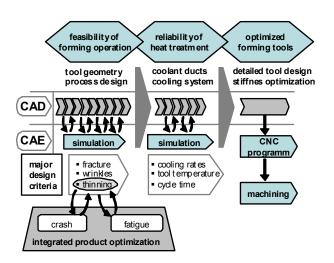

Fig. 1: Process and product optimization workflow in hotforming

Especially if the temperature distribution of the tools after a sequence of several production cycles is in the focus of interest an accurate consideration of all essential thermal boundary conditions and a detailed 3-dimensional tool model is absolutely necessary.

Regarding the different requirements mentioned above it is obvious to split the process into the two fundamental partial stages forming and cooling since this is in agreement with the typical workflow in

practice. In the forming stage the die designer modifies the geometry of the tool surface and the blank to meat the feasibility target. A volume mesh generation after each geometrical tool modification is absolutely unnecessary in this phase. By the use of a thick thermal shell element formulation in the thermal part of the solution the temperature increase of the tool surface in contact areas can be considered in coupled forming simulations. The tool surface temperatures after forming will be used as initial condition for the following cooling simulation. The cooling simulation can be performed as thermal only or also thermal-mechanical coupled. From a numerical point of view the split into two simulation steps becomes also very advantageous. Mass scaling and time scaling as typical approaches to reduce the cpu cost can be applied differently in each step. If the contact heat transfer is independent of the contact pressure the cooling simulation can be performed cpu cost efficient as thermal only. This procedure is preferable for thermal tool analysis after a sequence of production cycles.

3   Forming Simulation

Setting up a model for a coupled hotforming simulation should be similar to the known approach to set up a conventional sheet metal forming simulation. For the mesh of the tool surfaces the same typical geometric accuracy requirements need to be met. The tool surface should be able to change its temperature in areas of contact with the hot blank. Using a thick thermal shell element [1] is an adequate approach to account for this effect. The shell is geometrically represented by its mid plane (figure 2 left). With the parameter TSHELL this element is internally extended to a 12 node thick shell (figure 2 middle) by the thermal solver.
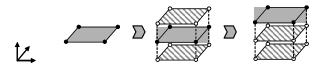

Fig. 2: Thermal thick shell element

An offset of the contact reference plane to the outer element plane enables the element to account for the temperature profile of the tool boundary layer using two additional nodes below the contact surface. The thermal contact can be described very accurate taking into account the contact heat transfer coefficient as a function of contact pressure and the contact gap. Figure 3 shows qualitatively the resulting curve if those dependencies are considered. The pressure dependency can be defined directly with an input curve or analytically using one of three implemented functions. These functions can also account for a temperature dependency.
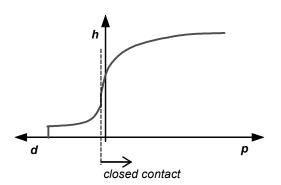

Fig. 3: Contact heat transfer coefficient h as a function of contact gap d and contact pressure p

The coupling of the thermal solution and the explicit mechanical solver follows a sequential approach. With this coupling method the thermal and the mechanical part of the problem can be solved independently using different solvers. The mechanical part uses a dynamic explicit solution scheme whereas for the solution of the thermal part an implicit conjugate gradient solver is used. In the dynamic explicit solution scheme the stable time step is limited by the Courant-Friedrichs-Levy condition. The elastic modulus of the typical boron steel used for hotforming varies approximately in

the range of 210 to 120 GPa in a temperature range between 20°C and 900°C. This effect accounts for 32 % change in the explicit time step.

$$\Delta t_{mech} \leq \frac{l}{c} \quad ; \quad c = \sqrt{\frac{E}{\rho\left(1 - v^2\right)}} \tag{1}$$

Even though an implicit time integration scheme is used in the thermal part the thermal time step is also limited. The thermal model must be able to respond as fast as the reality and so the maximum thermal time step is limited by the thermal diffusivity of the material, the element dimensions and the boundary conditions [2].

$$\Delta t_{therm} \leq \frac{1}{12} \cdot \frac{l^2}{a} \quad ; \quad a = \frac{\lambda}{\rho \cdot c} \tag{2}$$

In [3] it is demonstrated that for typical material properties of steel this thermal time step limit is some orders of magnitude above the explicit mechanical time step. Thus it is apparent to use the sequential coupling method and take advantage of the higher thermal time step to save cpu time. Another advantage of the sequential coupling method is that the contact becomes a linear boundary condition in the thermal solution. Thermal nonlinearities are usually caused by temperature dependencies of material properties and boundary conditions e.g. convection and radiation.
Instead of limiting the thermal time step by the use of equation (2) it has to be chosen small enough to track the changing contact situation due to the tool motion in the mechanical part. Thus with a given maximum tool velocity and a maximum tool travel between two thermal sub steps an upper limit for the thermal time step can be estimated straightforward.

$$\Delta t_{max} = \frac{d_{max}}{v_{max}} \quad ; \quad d_{max} = 1 \dots 5 \, \text{mm} \tag{3}$$

It is clear that the bottleneck in computation time is the explicit mechanical time step. A common technique to speed up the simulation is the application of both time and mass scaling. Time scaling is applied by using increased tool velocities. This approach is widely used since the material models typically used in sheet metal forming have no strain rate dependency. In contrast to this approach hotforming necessitates a material model with yield curves dependent to both temperature and strain rate. Thus the tool velocity in the real process must be known to quantify the time scaling factor. The rate dependency of the material has to be adapted to the applied time scaling. Due to the sequential coupling method all thermal velocity terms in the thermal part must be scaled accordingly. When applying time scaling to a thermal problem the dimensionless quantities fourier number Fo and biot number Bi must be in agreement with the real process.

$$Fo = \frac{\lambda \cdot t}{\rho \cdot c_p \cdot l^2} \quad ; \quad Bi = \frac{h \cdot l}{\lambda} \tag{4}$$

Increasing the tool velocity leads to a shortening of the time scale. This will be compensated by scaling up all thermal conductivities λ in the model by the ratio of the simulation velocity to the real velocity to keep Fo constant. If the thermal conductivities λ are scaled up all boundary heat transfer coefficients h must be scaled up in the same way to remain Bi unchanged.
Beside time scaling it is usual to enhance the performance of a forming simulation by the use of mass scaling. The default approach is to prescribe the time step for the entire simulation. Êlements with a critical time step lower than the prescribed one become mass scaled to meet the desired time step. During the forming simulation the mesh is refined by adaptive mesh refinement so that mass is permanently added. Typical time step sizes used in coldforming are 0.4 microseconds if the forming simulation is followed up by a springback calculation and up to 1 microsecond for formability analysis. Those values often are inconsiderately adopted for hotforming simulations. This can lead to erroneous results and will be demonstrated using a small example (figure 4).

Hotforming a strip of a channel is simulated using different time steps and the thickness reduction along a section cut is compared.
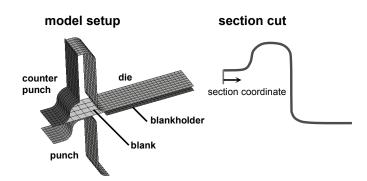
model setup   **section cut**

Fig. 4: Channel strip example

The tool velocity in the simulation is 10 m/s and is assumed to be 100 times faster than the real process. The high tool velocity together with higher mass scaling leads to a drastic overestimation of the thickness reduction (figure 5). Nevertheless in many cases those results seem to be reasonable because the friction in hotforming is very high and the yield strength of the hot material is rather slow. Thus an overestimated thinning may remain undiscovered in a feasibility study, especial if it locally occurs in regions where higher thinning is expected anyway.
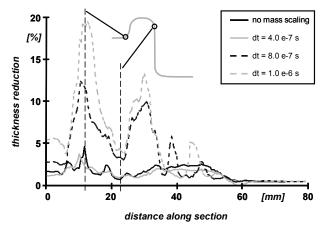

Fig. 5: Thickness reduction for different time step sizes

From the above results one can conclude that there is a higher sensitivity to both time and mass scaling in hotforming simulation. The reason is that in hotforming the blank is not clamped between die and blankholder. Unlike in conventional forming where the clamped blank is stretched over the punch to utilize the work hardening in hotforming the aim is to fold the blank around the punch curvature and keeping the thickness distribution as homogeneous as possible. Typically some areas of the blank therein perform rigid body motions similar to a flange in bending. Furthermore in hotforming the deformation is dominated by the wall areas where the material does not come into direct contact with the tools and remains at high temperatures during the forming operation. This leads to local minima of the current yield strength and the deformation concentrates on those weak regions. The weak unsupported material is very sensitive to non-physical yielding caused by inertia forces. Hence one should make a more conservative choice for both time step size and the amount of time.
In the recent version LS-DYNA offers an attractive alternative to use time scaling and substantial higher time steps without affecting the accuracy of the solution. This feature is called selective mass scaling and has been implemented by Olovsson [4, 5]. The basic idea is to add artificial mass terms such that the highest eigenfrequencies are decreased but the lower ones are affected as little as possible. Figure 6 shows the results for the channel example. Using selective mass scaling (sms) the solution with a time step size of 1 microsecond is in very good agreement with the reference without mass scaling. A further increase of the time step still leads to reasonable results. Since a penalty

contact is used the two solutions with higher time steps have a magnified numerical noise in the contact forces.
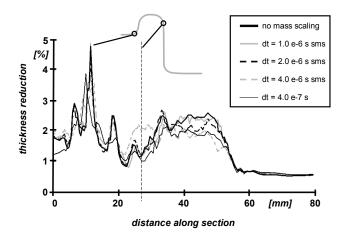

Fig. 6: Thickness reduction for different time step sizes with selective mass scaling (sms)

Nevertheless it should be noted those results are still comparable to a solution with a considerably lower time step using conventional mass scaling. It is obvious that with selective mass scaling the results are still reasonable even though the time step size is chosen in a range where the results with conventional mass scaling are insufficient.
Table 1 gives a survey of the performance enhancement for this example when using selective mass scaling.

Table 1: Total number of time steps and speed-up for the different variants

time step size	time steps	speed up
no mass scaling	58010	1.0
4.0 e-7 s	16655	2.9
8.0 e-7 s	8355	4.5
1.0 e-6 s	6684	5.4
1.0 e-6 s sms	6684	5.6
2.0 e-6 s sms	3342	9.0
4.0 e-6 s sms	1671	10.9

At a first glance it might seem astonishing that for 1.0e-6 s the speed-up is higher for the variant using selective mass scaling since this method normally requires more computational cost. In this case the difference is caused by the thermal sub problem which is solved in 82 thermal steps for the case with selective mass scaling and in 104 thermal steps for the case with conventional mass scaling.
The results from this little study apparently show that with selective mass scaling it is possible to run hotforming simulations much faster than using conventional mass scaling. In contrast to conventional mass scaling the quasi-static nature of a forming process is not violated and there is no loss in accuracy.

4   Cooling Simulation

The simulation of the cooling stage requires a 3-dimensional volume mesh to account for the heat dissipation into the tools. Furthermore the discretization of the tool surface has to fulfil the same accuracy requirements as for the forming simulation. Thus it would be quite simple if one can carry over the tool model from the forming simulation and extend it with a 3-dimensional mesh for the bulk material below the surface. This simple approach is demonstrated with the small channel example.

Figure 7 shows the tool model of the punch with the surface shell mesh from the forming stage and an additional volume mesh. The surface shell mesh and the volume mesh are connected with a thermal contact. If the cooling simulation is performed as thermal only the tools are rigid and the tool position is the final configuration of the previous forming stage.
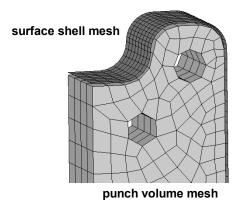

surface shell mesh

punch volume mesh

Fig. 7: Tool model with surface shell mesh

The tool motion in the forming simulation is typically controlled by a prescribed velocity and is stopped if the clearance between the tools reaches the initial blank thickness. In this case the contact heat transfer coefficient is only a function of the contact gap. If the pressure dependency as shown in figure 3 should be taken into account the cooling simulation has to be performed coupled. Since the duration of the cooling stage takes much longer than the forming stage the explicit time integration is not efficient and both mechanical and thermal part will be solved using implicit time integration. Nevertheless the coupling is still sequential. In this case according to the real process a force is applied on the moving tools to get the right contact pressure in the closed position. The tool surface shells are weak contact segments which are connected with a tie contact to the volume mesh. The volume mesh can be rigid or deformable. All three possible tool modelling approaches have been used in a cooling simulation of the channel strip.
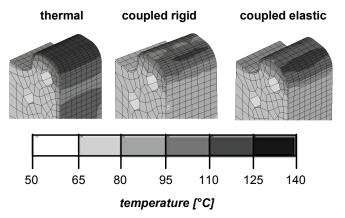

thermal   **coupled rigid**   **coupled elastic**

| 50 | 65 | 80 | 95 | 110 | 125 | 140 |

temperature [°C]

Fig. 8: Punch surface temperature after 1 s for different tool modelling approaches

The final temperatures from the forming simulation are used as initial conditions. For the thermal only simulation an intermediate constant contact heat transfer coefficient has been chosen and the critical gap width for closed contact has been set to 0.005 mm. For the coupled cooling simulations the critical gap was set to 0.001 mm and the heat transfer coefficient varies between 1100 and 5000 W/m^2K. Figure 8 shows the punch temperature after 1 second holding time in the closed tool. Since the thermal only model predicts in large areas of the contact surface a closed contact situation the heating of the punch surface is slightly overestimated compared to the coupled runs. The coupled model with a rigid volume mesh has a more inhomogeneous pressure distribution and thus the temperature fringes are not as smooth as in the elastic case. After 10 seconds holding time the results of the two coupled runs are nearly identical. The thermal only run showed higher surface temperatures, especially in the picked out radii region. The maximum deviation was about 20 °C. Table 2 gives an overview of the required time steps and cpu time for the small example. Nevertheless due to its

simplicity the thermal only approach might be accurate enough for a thermal die analysis where a sequence of production cycles will be ran one after each other. The deviations to the coupled runs will smear out during the transfer time between two forming operations where the surface heat diffused into the tools.

Table 2: Total number of time steps and cpu time for the different tool modelling approaches

	thermal	rigid	elastic
mechanical steps	-	29	35
thermal steps	86	102	111
cpu time [s]	1728	1900	2453

For a thermal die analysis the forming simulation is performed only one time to get the initial temperatures for the following cooling stages. After each cooling simulation the final tool temperatures are carried over as initial conditions for the next cycle. The blank initial temperature is always taken from the end of the forming stage. After several cycles the forming simulation can be repeated with new initial tool temperatures.

5   Cooling Passages

There are two possible ways to consider cooling passages in the tools. The simplest way is to define a convective boundary condition on the wall segments of the passage. This requires the average water temperature and the heat transfer coefficient between the water and the wall as input data. Since the passage is short and the flow rate is high the water might not heat up too much along the passage and thus the convection approach might be convenient. If the inlet temperature and the mass flow rate are given and the outlet is of interest the use of the new bulkflow feature can account for this. The bulkflow feature is a recent development in LS-DYNA and offers the ability of a simplified 1D-fluid flow calculation inside the thermal solver. Using the bulkflow feature the centreline of the passage is discretized with beam elements to account for the fluid flow. The fluid mass is concentrated on the nodes, the so called bulk nodes. The beams are wrapped by shells which represent the wall of the passage. This wall is connected to the solid tool with a thermal contact. Figure 9 shows this modelling approach in detail.
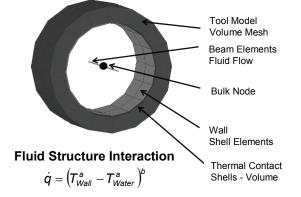
Tool Model
Volume Mesh

Beam Elements
Fluid Flow

Bulk Node

Wall
Shell Elements

Thermal Contact
Shells - Volume

Fluid Structure Interaction

$$\dot{q} = \left(T_{Wall}^a - T_{Water}^a \right)^b$$

Fig. 9: Representation of cooling passages

If a recent version of LSPrePost 2.2 is used one needs only an IGES or VDA curve of the centreline of the passage. The beams with wrapping shells and the required keywords are generated automatically. The use of the bulkflow feature is recommended for thermal tool analysis where the thermal response of the tools after several production cycles is in the focus of interest. Herein the mass flow rate through each passage can be varied to get a more homogenous temperature distribution in the tools.

6   Conclusions

Splitting the hotforming process into the partial stages forming and cooling is a very effective modelling approach in the simulation of hotforming processes. The sequential coupling method in LS-

DYNA makes it possible to use the explicit solver for the mechanical part and the iterative thermal solver for the thermal part to solve the coupled problem very efficient. It has been demonstrated that with selective mass scaling the required cpu time can be drastically decreased and the accuracy of the results is higher compared to conventional mass scaling with lower time step size. The extension of the forming model by an additional volume mesh for the tools turned out to be a simple and reliable approach to account for the calculations of the 3-dimensional heat flow into the tool during the cooling simulation. The use of a pressure dependent contact heat transfer coefficient in the cooling simulation gives more realistic tool surface temperature distributions but requires a coupled simulation. Due to its static nature and the long duration time for coupled cooling simulations the implicit mechanical solver should be used. For thermal tool analysis a thermal only simulation is faster, requires less memory and might be accurate enough. Dealing with a water cooling system in the tools the bulkflow feature is a quite simple to use method to account for the impact of the cooling system on the tools thermal response.

7   Literature

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