

# Simulation of Thermo-Mechanical Forming Process with LS-DYNA

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## **Abstract:**

In the recent past hot stamping simulation has established itself more and more within the press hardening community. However the requirements on a simulation software are continuously increasing due to an increasing complexity of the manufacturing processes. The focus in process simulation is not merely on the workpiece and its final properties, but also on the forming dies. To keep pace with all recent and even more with all future developments in press hardening LS-DYNA offers several features to deal with different aspects of press hardening processes. Nevertheless only a proper set of numerical parameters can make a simulation model an effective and efficient tool for a process designer. Based on recent experiences some useful parameter settings and modelling techniques are presented.

## **Keywords:**

metalforming, thermo-mechanical coupling, multiphysics

## 1 Introduction

Within the automotive industry the trend towards an increased application of ultra high strength steels for structural car body applications is continuing. During the last years the simulation of hot stamping processes has established itself more and more within the press hardening community. The results of the 2008 Numisheet benchmark have shown that feasibility studies of hot stamping processes can be performed with a sufficient accuracy. However the continuously increasing requirements from car body design have induced more complex press hardening parts which in turn require more complicated manufacturing processes. Thus different process strategies have recently been developed to manufacture parts with tailored properties such as partial austenization of blanks, tailored tempering with partially heated dies or advanced tool materials for a better control of the cooling effect. These continuous advancements of processes technology are raising the bar for a CAE based process development. The simulation technology must keep pace with all recent and even more with all future developments in press hardening. It is obvious that a close cooperation with customers is an indispensable prerequisite to achieve this goal. In the current Version R5 LS-DYNA has a lot of features to face the challenges of the up-to-date press hardening technology. Beside all this technological context an equally important point is often forgotten. A simulation software can only be a helpful tool for a process designer if a both effective and efficient method for model setup and process modelling is available. A prerequisite to set up an efficient process model is to figure out the main tasks of the actual development phase. An efficient simulation model deals with all necessary objectives of the respective task, but it should leave all other aspects of the process unconsidered. DYNAmore can offer a broad experience in modelling and simulation of thermal-mechanical coupled manufacturing processes and can help customers to find optimal modelling methods individually adapted to their processes and workflow.

## 2 Forming Simulation

Since the Numisheet2008 benchmark it is recognised that typical feasibility studies can be carried out with LS-DYNA. During the feasibility study the process designer checks if the thickness reduction is acceptable and if wrinkle formation during the forming operation is critical. The fundamental requirements for an accurate prediction of the thickness distribution is an accurate representation of the temperature and strain rate dependent yield stress of the blank material. Therefore an advanced table definition has been added to be used with MAT\_106. The temperature dependent quasistatic yieldcurves had been accessed by a DEFINE\_TABLE definition and the rate effects were considered by temperature dependent Cowper-Symonds parameters so far. A new keyword DEFINE\_TABLE\_3D has been implemented in the current version. DEFINE\_TABLE\_3D points for each temperature to a DEFINE\_TABLE definition with yieldcurves for different strain rates at a fixed temperature. Yieldcurves fitted from tensile test data can be written directly in the inputdeck.

In a real life press hardening process the hot blank remains for a few seconds on the lower die and/or binder until the upper die firstly hits the blank.

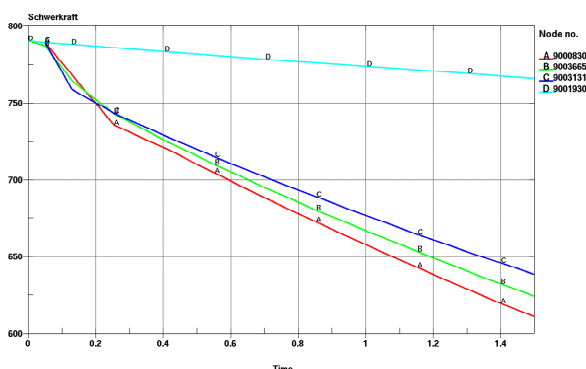


Figure 1: Temperature drop of  $\sim 100$  °C at support points (lower curves) during gravity simulation

This time period should be recognized in the simulation, because it can cause considerable temperature gradients in the blank. This is demonstrated in figure 1, where a 1.5mm thick blank remains on the binder for  $\sim 1.5$  s until the upper die impacts.

The best way to include this effect in a model is a coupled static implicit gravity simulation. Unlike in cold forming the mechanical solution should be done in several static implicit time steps. This works

well with an automatic time stepping in both thermal and mechanical solution using the keywords CONTROL\_IMPLICIT\_AUTO and CONTROL\_THERMAL\_TIMESTEP. The coupling scheme in LS-DYNA starts with a thermal time step since there are forcing boundary conditions in the initial state. It is beneficial to start with a small initial time step for both thermal and mechanical solution. As a rule of thumb  $0.005 \cdot \text{endtime}$  can be taken as initial step size.

The temperature rise of the die and binder at the support area be included with the thermal thick shell by setting TSHELL=1 on the CONTROL\_SHELL card ITHOFF=1 on CONTROL\_CONTACT. If the die surface heating is included it is mandatory to give all dies a reasonable thickness on the SECTION\_SHELL card. The thickness depends on the blank thickness and on the thermal conductivity of the tool material. A simple 1D-model can be used to calibrate the artificial thickness for the dies. The results for a 1.5 mm thick USIBOR blank against a die made of Rovalma HTCS-117 tool steel is shown in Figure 2.

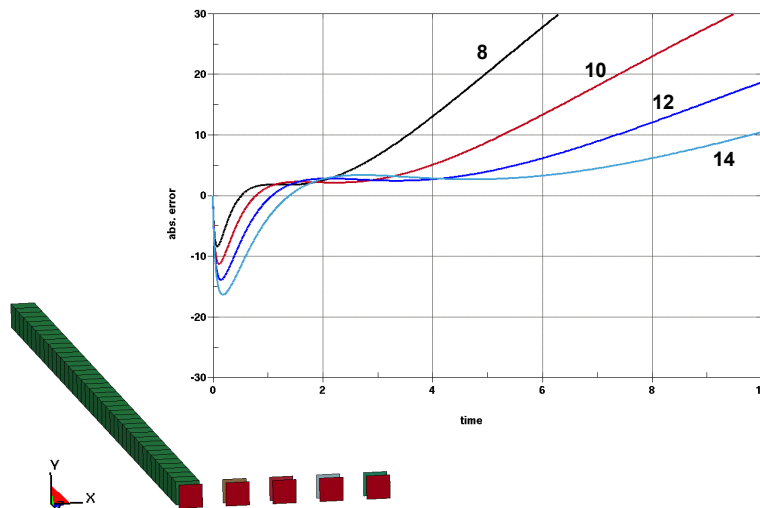


Figure 2: Calibration of artificial die thickness with simple 1D-model. Reference solid model left and four shell models with different thickness (8, 10, 12, 14 mm). Graph shows absolute error for shells.

A good compromise between small error for short and longer contact times is an artificial thickness of 10 mm, which gives a maximum absolute error of  $10^\circ\text{C}$  for the die surface temperature within 5 s contact time. The time period from insertion of the hot blank into the press to reaching bottom dead center is within 5s for most real life press hardening processes. Such a calibration takes a few minutes and it has the great advantage that the tool surface temperature is included in the analysis. This gives more accurate results for contact heat transfer with negligible additional CPU cost.

In some hot stamping processes a process designer has to cope with a realistic consideration of guide pins in his model (figure 3). The guide holes are in regions where a bigger hole will be trimmed after forming.

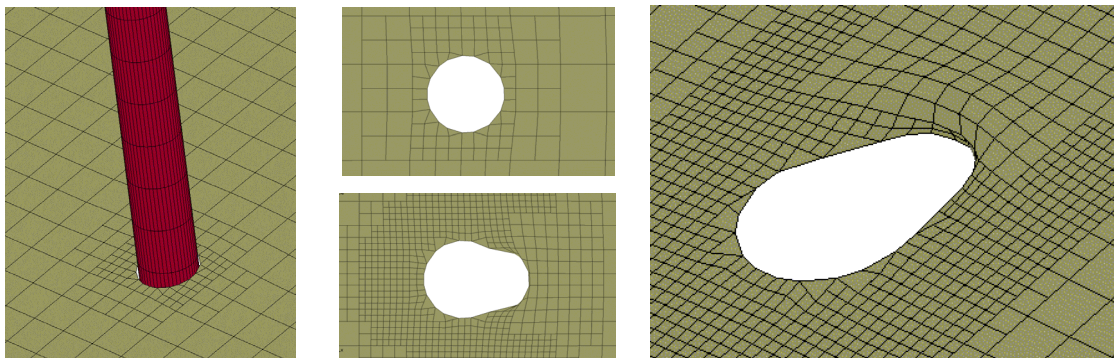


Figure 3: Consideration of guide pins in a hot stamping simulation. Blank with guide pin after gravity simulation (left), hole before and after forming (middle), deformed hole (right)

Due to the high temperatures during forming the blank material is weak and the guide holes can be severely deformed. The simulation must be able to predict if the deformed guide hole is still within the

trimcurve. The contact between the guide pin and the blank seems to be very difficult, but experience has shown that a FORMING\_ONE\_WAY contact is sufficient. To get the contact work properly a negative thickness offset of 110...150% of the blank thickness is necessary.

Another problem which can arise during a hot stamping simulation is severe element distortion in areas where the blank has a concave outline. In figure 4 such a situation is shown at a semicircular cut out for a guide pin. In this case the whole solution ran idle over night caused by one single element. The problem was solved by setting a critical plastic failure strain EFAIL=4.0 in the MAT\_106 definition.

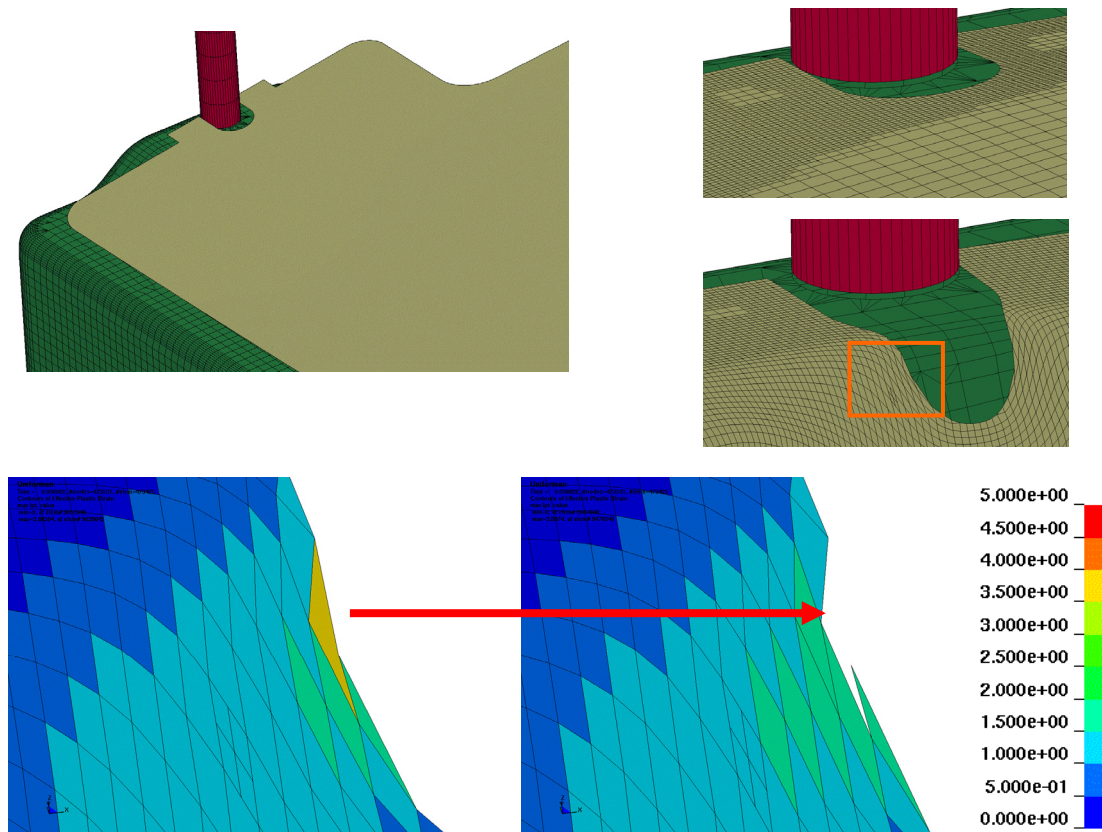


Figure 4: Severe Element deformation at a semicircular cut out. Blank with guide pin on the punch(upper left), cut out location in detail (upper right top), cut out after forming with critical area (upper right bottom), fringes of plastic strain with eroded element (lower)

This value is an unrealistic high number which will never be reached inside the blank. The deleted element is situated outside the final parts trimline, so there is no disturbing influence on a feasibility study. With the activation of element erosion the job ran within 3 hours even with a high level of mesh refinement.

A great simplification in model setup can be achieved if as demonstrated in [1] the new keyword CONTROL\_FORMING\_AUTOPOSITION\_PARAMETER is used together with PART\_MOVE to automatically position the dies to initial contact with the blank. The user has to provide only the meshes of the dies in the bottom dead center position. All positioning is done by LS-DYNA during the initialization. Since each travel distance from auto positioning is stored in a parameter, this parameters can be accessed e.g. within a DEFINE\_CURVE\_SMOOTH definition to prescribe the die velocity. It should be noted that the auto position keywords must be located after the ELEMENT, NODE and PART keywords.

A well defined model can become a very useful tool for a process designer, but only if it runs CPU cost efficient. Within the metal forming community it is state of the art to reduce CPU time by both time and mass scaling. Time scaling is applied by increasing the die travel velocity up to 5 m/s. Mass scaling is introduced to increase the critical time step. In a thermal-mechanical coupled simulation the thermal

model has to be scaled according to the mechanical model. Thus the real die velocity in the press must be known. The velocity scale factor can be directly entered in CONTROL\_THERMAL\_SOLVER as parameter TSF instead of manually scaling all thermal velocity terms in the input file. A drastic performance increase can be achieved by using selective mass scaling [2, 3] and run the model with very high explicit time steps. In [4] an example is discussed in detail which shows that with this feature a model can be ran much faster without loosing any accuracy, as it would be the case for conventional mass scaling. The selective mass scaling is invoked by setting IMSCL=1 on the CONTROL\_TIMESTEP card. The time step size can be increased to 2...8  $\mu\text{s}$  in a forming simulation, but the sliding energy in the glstat file should be observed with care. In some cases the sliding energy went negative indicating a contact instability. In this cases the penalty scale factor should be reduced. As a rule of thumb one can set SLSFAC=0.05 in CONTROL\_CONTACT, if selective mass scaling is used with a high time step size of 2...8  $\mu\text{s}$ .

### 3 Cooling Simulation

The model setup of a cooling simulation can become very time consuming if a detailed heat transfer analysis of the forming dies should be carried out. Therefore the dies must be represented with a 3-dimensional volume mesh. The meshing can become very complicated because of the complex internal geometry of the cooling system. Furthermore the mesh of the contact surface should be as fine as in a forming simulation in order to accurately describe the contact situation between die and blank. A simple and effective method is to mesh the dies with tetrahedron elements with an adequate mesh size for heat transfer. For the contact surfaces of the dies the shell meshes from the forming simulation can be used. Each die consists of 2 parts, the surface shells and the volume mesh. Both parts can be connected using CONSTRAINED\_RIGID\_BODIES keyword. In addition thermal contact is necessary to enable a heat dissipation from the surface shells into the volume mesh. This can be done by using an AUTOMATIC\_ONE\_WAY\_SURFACE\_TO\_SURFACE\_THERMAL contact and setting the heat transfer coefficient HCONT to  $5.0\text{e}+4 \text{ W/m}^2\text{K}$ . Figure 5 shows a model setup for an A-pillar cooling simulation. The model consists of 284602 shells, 2946238 tetrahedrons and 634193 nodes. Since the contact heat transfer coefficient is a function of the contact pressure the model must run thermal-mechanical coupled in to get an accurate prediction of the heat transfer from the blank into the dies. The mechanical solution was run in explicit mode with a high amount of mass scaling. Since we have no free motions there is no danger of unphysical inertia effects.

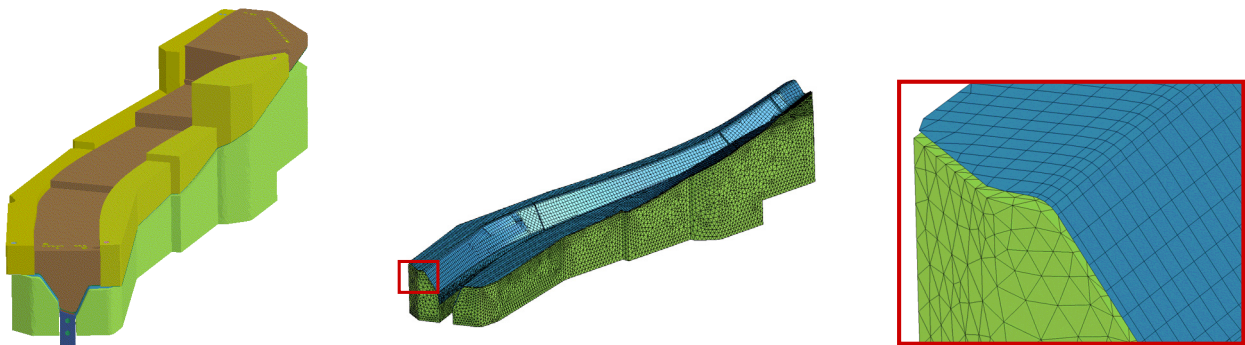


Figure 5: 3D model of a cooling simulation. Full set of dies (left), surface and volume meshing of lower die (middle), detail view of surface and volume meshing (right)

The total CPU time was for this model was 20 minutes using mpp971\_d\_R5.0 on one 8 CPU node. Compared to the time consuming mesh generation the computation time of a cooling simulation can be neglected. The most important parameter settings in the model are the explicit time step size, ramped up press forces and the application of rigid body stoppers. The simulation must be regarded in two major phases. In the first face the forces are ramped up and the contact forces reach the stationary level. In this phase to high amounts of mass scaling can negatively influence the generation of the contact forces. In the second phase the contact forces are stationary and the kinetic energy can be neglected. In this phase the time step size and thus the amount of mass scaling can be drastically increased. This is done with a load curve prescribing the time step over the solution time.

With this efficient cooling model it is possible to run several cooling cycles to analyze the process start up time. Such a simulation can give a deeper understanding of the cooling system. The result of a the A-pillar tool after 10 strokes is shown in figure 6. The cooling system has been modelled by convection

boundary conditions on the cooling passage surfaces. The convection coefficients were calculated with the Dittus-Boelter equation as shown in [5]. The use of this equation is a conservative approach since it is for perfectly smooth pipes. In a technical rough pipe the convection coefficients are higher due to a friction correction factor.

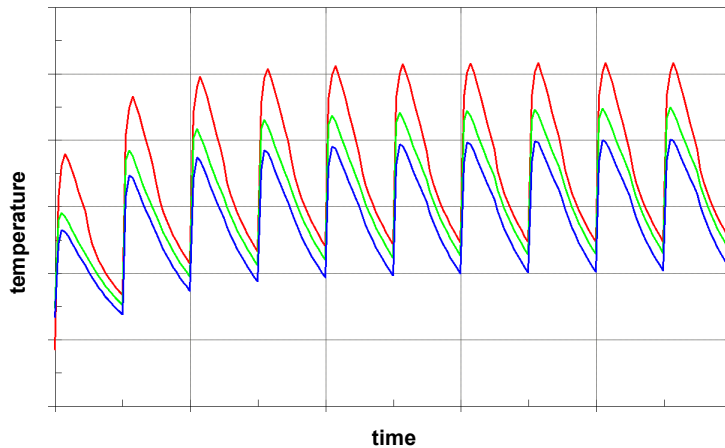


Figure 6: die surface temperature at 3 different locations after 10 strokes

At 3 significant locations on the die surface the evolution of the surface temperature shows that a steady state can be reached within a few strokes. This result demonstrates that the cooling system works very effectively. The simulations have been automatically started one after each other using a simple shell script. After each simulation a time shift has been applied on all d3plot files using the DYNAmore tool plotcprs. Finally the d3plot files were renamed and copied all together.

#### 4 Advanced Cooling Simulation

The main target in each press hardening process is to achieve a predefined microstructure in the final part. LS-DYNA offers the new material model MAT\_UHS or MAT\_244 [6] to consider the decomposition of the austenite into the bainite pearlite and ferrite phase during press hardening. This enables the process designer to adapt the cooling effect to give the final product more strength or more ductility. The material model can predict the vickers hardness number and the yield strength of the final product. It requires the chemical decomposition of the used steel grade, the austenite grain size and the activation energy of the diffusion driven phase change reactions. The model is absolutely necessary if advanced press hardening processes which aim to parts with tailored properties should be analyzed in detail by simulation. If MAT\_UHS is used in a simulation no time scaling of the mechanical model is allowed since the reaction kinetic inside the material can not be time scaled. Nevertheless if an ordinary hardening process is analyzed where the aim is a fully hardened part a simple analysis of the parts local cooling curves with a CCT diagram is sufficient.

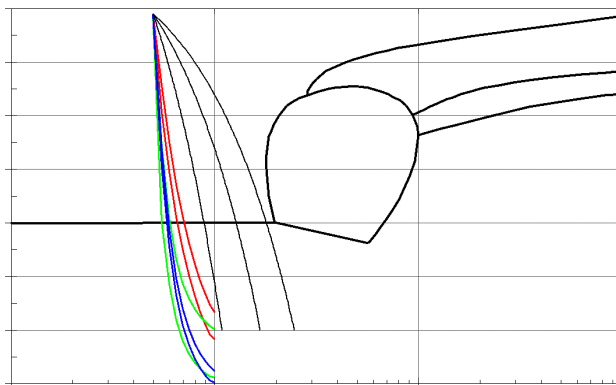


Figure 7: Cooling curves plotted in CCT diagram

In figure 7 the cooling curves at 3 noticeable points of the A-pillar are printed in a CCT diagram of the blank material. Since the cooling curves are in a safe distance from the bainite nose it can be

concluded that the part is completely hardened. In this case the use of MAT\_UHS would be using a sledge-hammer to crack a nut.

Beside the cooling of the dies in recent developed process technologies a partial heating of the dies is required to control the cooling effect of the blank. Therefore LS-DYNA offers the keyword LOAD\_HEAT\_CONTROLLER where a PI-controlled heat source can be applied. In the recent version of ls971\_d\_R5 up to 10 heat controllers can be used. The control function is

$$\dot{q}''' = \dot{q}_0''' + G_P (T_{set} - T_{node}) + G_I \int_{t=0}^t (T_{set} - T_{node}) dt$$

The required user input are the proportional and integral gain, a set point temperature and the node ID for the location of the set point.

## 5 Conclusions

It has been shown that with an adequate choice of modelling features together with a proper set of numerical parameters a simulation model can become both efficient and accurate. Some special program settings for gravity and forming simulations were presented. Some stumbling blocks in hot stamping simulation were pointed out and pragmatic remedies were described. Some experiences of the computational performance in a real life process simulation were outlined. Finally the use of the advanced material model MAT\_UHS and the use of LOAD\_HEAT\_CONTROLLER for local die heating were discussed.

## 6 References

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