B. Active Flexible Binder Control System for Robust Stamping

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Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objective

- Develop, build and demonstrate an optimized closed-loop flexible binder control system that can be installed in stamping presses to improve the quality of panels made from aluminum alloys and high-strength steels and to reduce the cost for developing and setting production tools.

Approach

- Conduct open-loop control demonstration of flexible binder technology.
- Develop methodology and guidelines for designing and building flexible binders.
- Develop computer simulation and process optimization capabilities for flexible binders.
- Develop a closed-loop flexible binder control system with appropriate sensors.
- Demonstrate closed-loop control of the flexible binder system on an industrial part.
- Evaluate the technical and economic feasibility of flexible binder technology.

Accomplishments

- The retrofitted Erie Press Binder Control Unit and GM liftgate tooling were tested in tryouts at TDM in Warren, MI using three different materials with varying thicknesses. Binder force trajectories generated by both trial-and-error and FEA were implemented and parts were successfully made. The tryout time using the system was considerably less than the estimated tryout time using conventional methods of working the die.
- A new 10-cylinder IFU binder control unit with pan tooling was tested successfully in a hydraulic press at the University of Stuttgart in Germany. Tests in a mechanical press, which are crucial to demonstrating the

applicability of binder control technology in mechanical systems, are scheduled at TDM in Warren, Michigan during November/December 2005.

- Three materials (A6111-T4, DP500 and BH210) were tested under biaxial deformation using the Viscous Pressure Bulge (VPB) test. This test yields more accurate information compared to the uniaxial tension test because stress conditions in stamping are often different from the ones present in the tensile test. Flow stresses from the test are used as input for FE simulation of the stamping process.
- Closed-loop control tests were run using the IFU unit equipped with wrinkle height sensors. The feedback controller was successful in maintaining the imposed wrinkle height limit by modulating the binder force on the six active cylinders. Test results show clearly that closed-loop control can produce a significant improvement in the quality of the drawn pan.
- FE simulation and optimization programs were applied to the GM liftgate and optimum blankholder forces (BHF) that are variable in space and constant in stroke have been obtained for A6111-T4. The optimization program, which was designed to run on Ohio State University's (OSU's) HP Unix, has been modified to run on GM's Sun Solaris operating system. The program was tested at GM as part of the verification and technology transfer plan.

Future Direction

- Conduct trials and demonstration on the GM liftgate using optimized BHF trajectories that varies in location and stroke.
- Conduct closed-loop trials and demonstration in a mechanical press using a new 10-cylinder binder load control unit equipped with feedback control system and wrinkle height sensors.
- Quantify technology benefits based on TDM's experiences with the flexible binder control system.
- Transfer developed technologies to OEMs and suppliers.
- Develop a commercialization plan including methods for efficient packaging and integration of hydraulic, electrical and control components.
- Identify commercial applications.
- Develop a business case for using this technology in the automotive industry.

Introduction

Traditional stamping uses rigid binders that do not address local forming conditions. Also, it cannot respond to process variations that may lead to stamping inconsistencies or even failure. Significant weight saving can be achieved by replacing parts made from mild steel with those made from lightweight and high specific-strength materials such as aluminum alloys and high-strength steel. But such materials are less formable and result in higher springback than mild steel. Forming such materials require innovative tooling and advanced controls.

Advanced binder load control systems can improve stamping quality, increase part consistency and reduce the time and cost for fine tuning of stamping tools. This new technology will have a significant impact on the US stamping industry.

One major task of this project was to retrofit the Erie Press Binder Control Unit to enable accurate binder load control in all 26 hydraulic force actuators. The unit has originally been fitted with a Xycom digital control system; however, poor performance and instability were observed during operation because the Proportional Integral Derivative controller could not handle the large flow-rate variation caused by the variable velocity profile of a mechanical press. Over the last three years, the project successfully developed and implemented an advanced control system for the unit based on mathematical modeling, computer simulation and experimental testing. The system hydraulics was repaired and the electrical system was rewired and retrofitted with a digital real-time control system and appropriate signal conditioning electronics. The unit was tested in a press at TDM using the GM liftgate tooling.

The Institute of Metal Forming at The University of Stuttgart (IFU) collaborated with two industrial suppliers in Germany, HYDAC and MOOG, to build a new binder load control unit equipped and instrumented with a large collection of advanced features: ten specially designed hydraulic cylinders, twelve proportional valves, two encoders for cushion position, one encoder for ram position, four punch force sensors, one wrinkle height sensor, one flow in sensor and one friction sensor. The unit has state-of-the-art cylinders, valves and controls. It also has three types of sensors for use in closed-loop control of the binder in a mechanical press environment. Testing of the unit in a hydraulic press in Germany has been completed. The IFU unit has been shipped to TDM in Warren, Michigan for installation in a mechanical press. Demonstration of the unit is scheduled for November/December 2005.

The Blankholder (BH) applies appropriate restraining force on the sheet metal blank to suppress wrinkles and eliminate splits during forming. Many studies have shown that variable blankholder force profiles increase the formability of stamped parts. In this project, Adaptive Simulation (AS) and Optimization (OPT) methods, coupled with FEM simulation, were developed and used to predict optimum constant and variable blankholder force (BHF) trajectories in single and multi-point cushion systems to reduce thinning and springback in the IFU part and the GM liftgate inner. FEM simulation and optimization programs were applied to the GM liftgate and optimum (BHF) trajectories that are variable in space and constant in time have been obtained. The optimization program, which was designed to run on OSU's HP Unix, has been modified to run on GM's Sun Solaris operating system. The program is being tested at GM as part of the technology transfer effort of the project. The simulation/optimization programs have also been converted to run on PAMSTAMP and LSDYNA software.

The following is a brief description of the work accomplished in the various tasks of the project.

Task 1: Conduct Open-Loop Control Demonstration of Flexible Binder Control Technology

1. The Erie Unit

Figure 1 shows the Erie Unit with the liftgate tooling installed in a mechanical press.

The tooling consists of an upper die, lower punch, inner blankholder, outer blankholder and guide for outer blankholder. The upper die, lower punch and the inner blankholder are made from Zn alloy (Kirksite material) commonly used in making prototype dies for stamping. The outer blankholder is made of cast iron using the segmented elastic blankholder concept developed by the University of Stuttgart (IFU). The inner and outer blankholders are attached to the 26-cylinder cushion system. Force applied by each cylinder can be independently adjusted and controlled during the stamping process. The required blankholder force is provided by the multipoint cushion system rather than the cushions in the press.

The die and punch geometry was initially designed by GM for use in a conventional rigid binder to stamp 1-mm-thick aluminum A6111-T4 liftgates using single-point cushions/nitrogen cylinders. However, the liftgate part could not be formed from A6111-T4 material with rigid blankholder despite several days of tryouts employing spotting the dies and adjusting the binder force in all the cushions.

Figure 1. TDM mechanical press with the 26-point cushion system (Erie Unit) and the GM liftgate tooling.

The die geometry was later modified by GM to form the part in production from 5xxx series aluminum alloy. Due to the complexity and difficulty in manufacturing the liftgate from A6111-T4 alloy, the die geometry was selected for the advanced binder control project to demonstrate the ability of multi-point cushion systems to solve difficult stamping problems. For this project, the conventional outer blankholder in the liftgate die was replaced by the segmented elastic blankholder developed by IFU. Also, the multipoint cushion system built by Erie Press was also used.

The retrofitted Erie unit with the liftgate tooling was installed in a TDM mechanical press and tested using both constant and time-varying blankholder force (BHF) trajectories. Liftgate panels were successfully made from BH210 steel, DP500 steel and A6111-T4 aluminum using the same set of tools.

The tryout time using the system was considerably less than the estimated tryout time using conventional methods of working the die. For example, the BH210 part was made in about 4 hours compared to about 5 days with die work, while the aluminum part was made in about 3 days. Splits could literally be healed in minutes by adjusting the tonnages of the appropriate cylinders. Prior efforts to make the part with aluminum A6111-T4 using conventional methods were unsuccessful.

Figure 2 shows liftgate inners made from BH210 (upper left) and DP500 steel (upper right). In both cases, the parts were formed without any splits on the first hit. However, there was some wrinkling which was corrected by trial-and-error adjustment of the cylinder tonnages.

In addition, binder force estimates from FEA were used for the tryout of aluminum. The FEA data for the 1.0 mm blank were provided by OSU while the FEA data for the 0.9 mm blank were provided by Alcoa. The 0.9 mm blank was 25 mm shorter in height. The OSU data were constant in stroke (time) but variable in space while the Alcoa data were variable in both space and time.

Figure 2 also shows the aluminum parts made using the OSU (lower left) and Alcoa (lower right) FEA

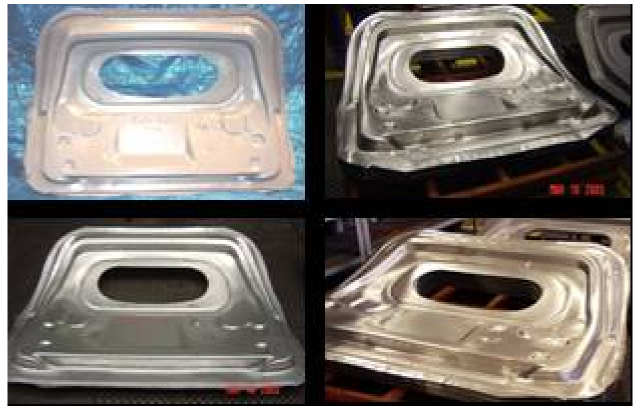

Figure 2. Liftgates made from BH210, DP500 and A6111-T4

simulation. The OSU simulation also predicted the observed side-wall wrinkling.

This task was completed with a successful demonstration of the unit to the project participants.

2. The IFU Unit

The IFU binder load control unit was built in Germany by a consortium which includes the University of Stuttgart, MOOG, HYDAC and the USCAR. The components of the unit were assembled and installed in a 20,000 kN hydraulic press at IFU in Stuttgart for validation and testing. Figure 3 shows the IFU unit in the hydraulic press. Figure 4 shows a more detailed picture of the flexible binder unit with the pan tooling.

The IFU unit has an easy to use Graphical User Interface (GUI), shown in Figure 5, to create, edit and upload a configuration file containing the force-

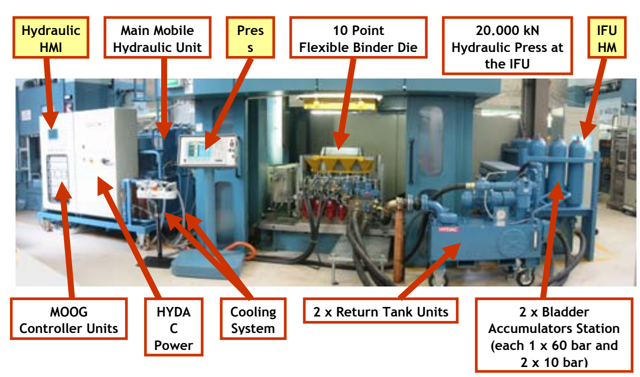

Figure 3. The IFU unit in a hydraulic press.

Figure 4. The flexible binder die in the press.

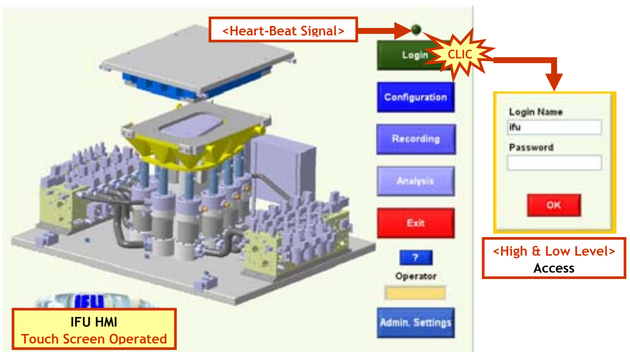

Figure 5. The IFU graphical user interface.

versus-stroke profile. The GUI was designed in LABVIEW to operate in combination with a touch screen. The unit operator needs only to login to access the configuration menu. The program has two operator levels. The high level gives the user access to the recorded data in order to perform data analysis.

IFU Test Results

a. Control System Tests

IFU ran tests to verify that the pressure control system can track all command trajectories. Figure 6 shows an example of a flawless tracking force-versus-stroke trajectory in cylinder #5 at a slide velocity of 300 mm/s.

b. Closed-Loop Tests

IFU has performed tests on closed-loop control using wrinkle height sensors. The tests were run with and without closed-loop control to show that the closed-loop system can actually modulate the

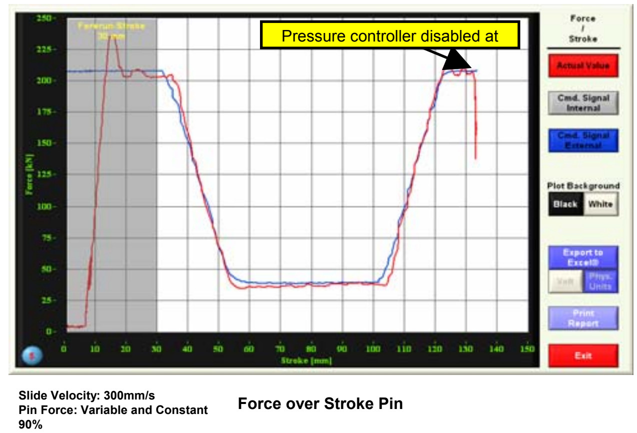

Figure 6. Force versus stroke trajectory.

binder force in-process to produce wrinkle free pans. The first set of tests was performed using IFU's hydraulic press in Stuttgart at a slide velocity of 20 mm/s without activation of the closed-loop control system. To produce wrinkles in a mild steel pan, a small binder force of 6 kN was applied to each of the six activated cylinders. This situation produced wrinkles so high (over 10 mm) that the drawing process had to be stopped at a depth of 100 mm for fear of damaging the die. In the second set of experiments, the 6 kN load was maintained on the six active cylinders, but this time the closed-loop control system was activated. A small constant wrinkle height value of 6 mm was set as a limiting wrinkle height that should not be exceeded. The controller was successful in maintaining the imposed limit by modulating the binder force on the six cylinders.

Figure 7 shows clearly that closed-loop control can produce a significant improvement in the quality of the drawn pan.

Status of the IFU Unit

The IFU Binder Control Unit has been shipped to the US for installation in a mechanical press at TDM in Warren, Michigan. Tryouts and demonstration of the unit are schedule for November/December 2005.

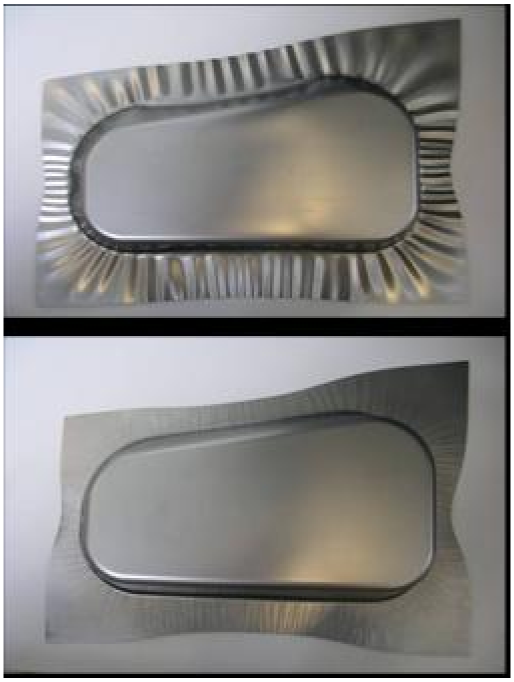

Figure 7. Pan drawn without (upper photo) and with (lower photo) closed-loop control.

Task 3: Develop Computer Simulation and Process Optimization Capabilities for Flexible Binders

a. Determination of Formability and Flow Stress Sheet Materials Using the Viscous Pressure Bulge Test

In stamping, the material properties of the sheet material (i.e., flow stress curve) greatly influence metal flow and product quality. This information is necessary as an input for Finite Element (FE) simulation of stamping processes. Usually the incoming material is tested using a uniaxial tensile test because this is a simple and inexpensive standardized test. Stress conditions in stamping are often different from the ones present in the tensile test. Therefore, it is useful to test the material under biaxial deformation conditions using the Viscous Pressure Bulge (VPB) test. Test equipment for VPB test is shown in Figure 8. A burst specimen for A6111-T4 is shown in Figure 9.

The maximum effective strain achievable in the VPB test without local necking is much larger (usually twice) than that in the tensile test. Flow stress estimated by VPB test would be used in the

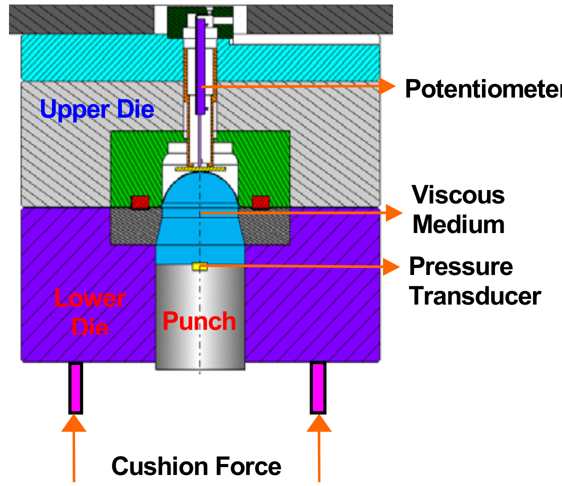

Figure 8. Test equipment for the Viscous Pressure Bulge (VPB) test.

Figure 9. A burst specimen of A6111-T4.

FE simulation to estimate the required blankholder force for forming the liftgate part.

To determine the flow stress of the sheet material, the instantaneous pressure, the dome height, the radius of curvature of the dome, and the thickness at the top of the dome are required. The instantaneous pressure and dome height are obtained from experiments while other parameters are obtained from a database. The database was generated through finite element simulation of the VPB test for different values of strain hardening index (n).

The flow stress and the formability of 1-mm (0.0394- in)-thick aluminum alloy A6111-T4, 0.8-mm (0.0315 in)-thick Dual Phase steel DP500 and 0.81-mm (0.0319 in)-thick Bake Hardened steel BH210 sheet material were determined using VPB test. Figure 10 shows the flow curves of DP500, BH210 steel and A6111-T4. The figure shows that the flow stress for DP500 is higher followed by BH210 steel and A6111-T4 for any given strain value. This indicates higher strength exhibited by DP500 compared to BH210 steel and A6111-T4.

Figure 10 also shows that the maximum strains obtained from the bulge test for DP500, BH210 steel and A6111-T4 are 0.57, 0.60 and 0.41, respectively, indicating higher formability of BH210 steel followed by DP500 and A6111-T4.

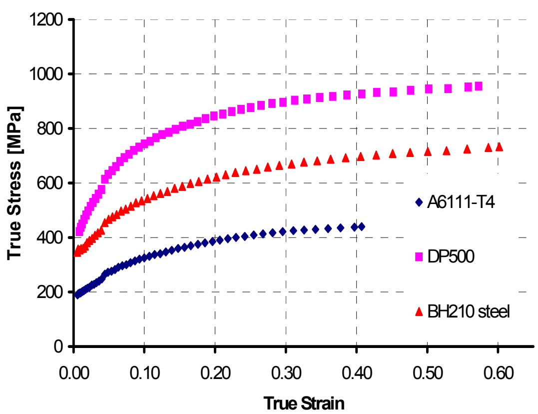

Figure 10. Flow curves for three materials determined by the VPB Test.

The dome height and pressure are measured during the experiment in real time. A press speed of 8 mm/sec was used for testing all the materials. However, the forming speed and strain rate do not affect the results significantly since the tests are conducted at room temperature. The dome height at bursting can accurately be obtained by monitoring the rapid drop in the pressure of the viscous medium. The measured dome height is an indication of the formability of the material. The consistency in the measured dome height and the burst pressure indicates that the quality of the incoming sheet material is also consistent. The average dome heights for the three materials are shown in Figure 11. As expected, the average dome height agrees with the known formability of the three materials.

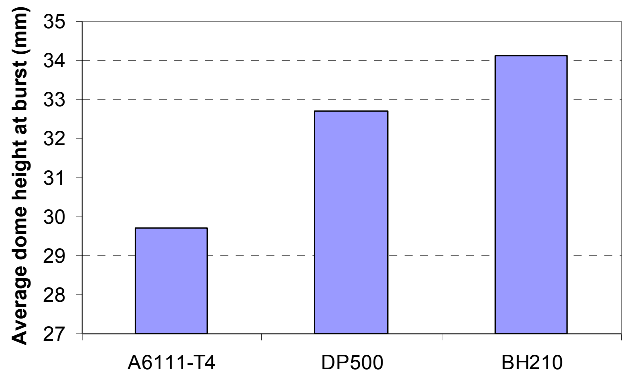

Figure 11. Average dome height for three materials measured by VPB Test.

b. Estimation of Blankholder Force Variable in Space and Constant in Time for theLiftgate Part

The FE simulation of the stamping process for the liftgate was conducted in three stages similar to the stamping operation in a single action tooling.

Stage I - Gravity simulation: The deformation of the sheet due to its own weight when placed on the blankholder.

Stage II – Holding simulation: Clamping of the sheet between the blankholder and upper die was conducted in two steps. In step I of the holding simulation, the sheet was clamped between the blankholder and the die by the movement of the upper die against the blankholder. In step II of the holding simulation, the sheet was clamped between the blankholder and the die with a gap of sheet thickness by applying force boundary conditions on the blankholder.

Stage III – forming simulation: In the forming simulation, the punch is moved against the die in the FE simulation to form the sheet to the desired shape.

The liftgate die consists of 26 independently controlled hydraulic cylinders. FE simulations coupled with optimization technique were used to estimate the optimal blankholder force in each cylinder to form the liftgate part. Due to symmetric boundary conditions, only 15 cylinder or cushion pins (pin 1 – 15) would be considered in the analysis.

Use of multipoint cushion system in stamping allows four possible modes of applying blankholding force during the forming process:

1. Constant in space and stroke: Constant blankholder force in all the pins that do not change during the punch stroke.
2. Constant in space and variable in stroke: Constant blankholder force in all the pins that change during the punch stroke.
3. Variable in space and constant in stroke: Different blankholder force in each pin that does not change during the punch stroke.
4. Variable in space and stroke: Different blankholder force in each pin that change during the punch stroke.

FE simulation coupled with optimization was used to predict the blankholder force varying in space and constant in stroke for liftgates made from 1-mm-thick aluminum alloy A6111-T4 sheets. Predicted optimized blankholder forces are given in Figure 12 and the corresponding pin locations are shown in Figure 13.

Currently, thinning and wrinkling are the only parameters used to monitor part quality.

Thinning Distribution Results

Figure 14 shows the thinning distribution predicted by FE simulation for the optimized blankholder force. Optimum blankholder force varying in space and constant in stroke resulted in maximum thinning of approximately 24%.

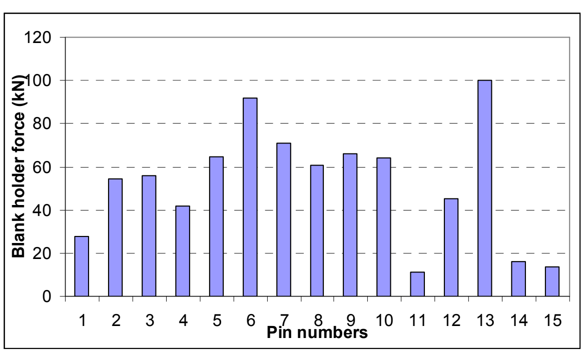

Figure 12. Predicted blankholder force variable in space and constant in stroke.

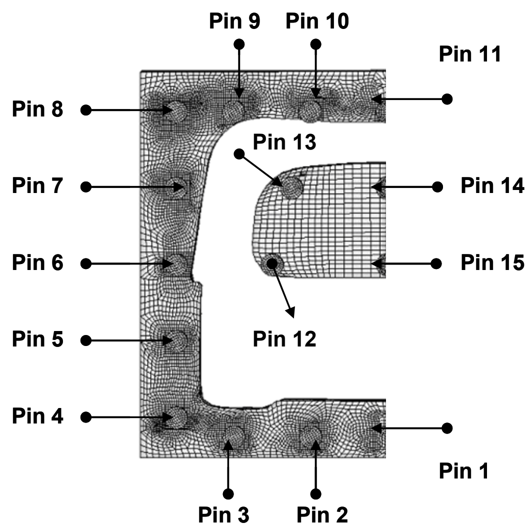

Figure 13. Pin locations in the liftgate simulation.

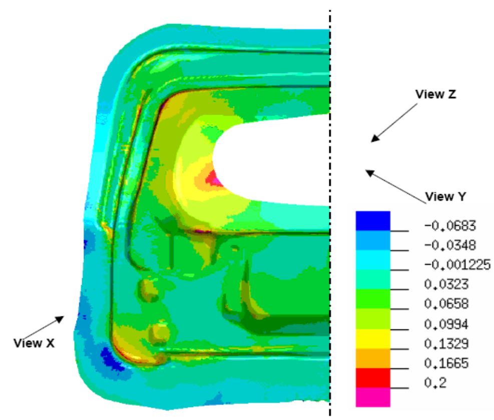

Figure 14. Thinning distribution predicted by FE simulation.

Wrinkling Results

Figure 15 shows possible location of wrinkling in the part for the predicted optimum blankholder force varying in space and constant in time. In the FE simulations, wrinkling was observed in the part at detail (A) in the Figure.

Further increase in the blank holder force did not result in elimination of wrinkles but increased thinning in the part. Even a large blankholder force of 125 kN in all the pins could not get rid of the wrinkles. This could be due to differences in the geometry between the FE model and the physical die at the wrinkle location.

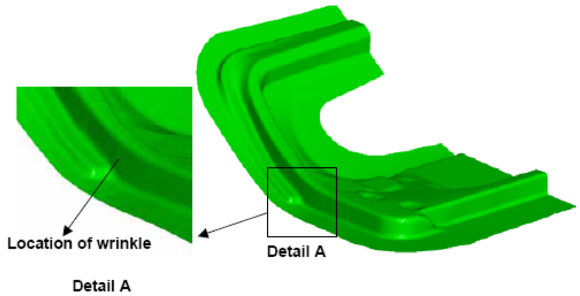

Figure 15. Locations of wrinkling in the part predicted by FE simulation.

Experimental Validation of BHF Profiles

Experiments/tryouts for forming the liftgate were conducted in a mechanical press at TDM using the multipoint cushion system and the flexible binder. Optimum blankholder force variable in space and constant during the stroke predicted by FE simulation coupled with optimization techniques was used in the tryout to form the part and validate the FE predictions.

Figure 16 shows the A6111-T4 blank geometry of thickness 1 mm used in the experiments/tryout. The edges of the blanks were deburred to avoid cracking during forming due to defects in blanking and piercing from the coil. The sheets were lubricated with dry thin-film lubricant precoated on the coil from the rolling mill.

Figure 17 shows that the liftgate was formed without splits. However minor wrinkles were observed in the flange geometry beyond the drawbeads on top and bottom and on one of the corners. Experiments carried out with very high blankholder force could not eliminate the wrinkles

Figure 16. Blank from A6111-T4 used in liftgate tests.

Figure 17. Successfully formed liftgate.

in the flange as observed in FE simulation. This further validates the FE model.

Major conclusions from the simulation study are:

- Predicted optimum blankholder force resulted in maximum thinning of 24 % in the part. Also, wrinkles were observed in the part.
- Wrinkling in the part predicted by FE simulation was found to be insensitive to the blankholder force. Even high blank-holder force of 125 kN did not result in elimination of the wrinkle.
- Tryouts on the liftgate verified FE simulation predictions. The panels were produced with minor wrinkles and no splitting.

Conclusions

The Erie Press Flexible Binder Unit was retrofitted with an advanced control system for hydraulic pressure control in all 26 cylinders. The unit was repaired hydraulically and retrofitted electrically to enable the control system to be effectively integrated. Binder force trajectories generated by both trial-and-error and FEA were implemented and liftgate panels were successfully made from BH 210 steel, DP 500 steel and AL 6111-T4 aluminum. The project was completed with a successful demonstration of the unit.

The new, 10-cylinder IFU binder control unit with pan tooling was tested successfully in a hydraulic press at the University of Stuttgart in Germany. Tests in a mechanical press, which are crucial to demonstrating the applicability of binder control technology in mechanical systems, will be conducted at TDM in Warren, Michigan.

Closed-loop tests show clearly that feedback control can produce a significant improvement in the quality of drawn pans.

FE simulation coupled with optimization technique was used to successfully predict the blankholder force varying in space and constant in stroke for the 1.0-mm-thick aluminum alloy A6111-T4 liftgate. The next step is to predict optimized blank-holder forces varying in both space and time.

Presentations and Publications

1. **Prediction of Blank Holder Force in Stamping Using Finite Element Analysis**
   Hariharasudhan Palaniswamy*, Arunkumar Thandapani*, Srikanth Kulukuru* and Taylan Altan*
   *ERC for Net Shape Manufacturing, The Ohio State University, 339 Baker Systems, 1971 Neil Ave, Columbus, OH, 43210, USA
   Presented and published at NUMIFORM Conference, Columbus, OH, May 2004

2. **Springback Control With Variable Binder Force – Experiments And FEA Simulation**
   Changqing Du*, Jin Wu*, Marcio Militisky¶, James Principe¶, Mark Garnett†, Li Zhang*
   *DaimlerChrysler, Advance Manufacturing Stamping Engineering
   ¶DaimlerChrysler, Body Material Engineering
   †DaimlerChrysler, Advance Manufacturing Engineering, Core Group
   Presentation and publication at the SAE Congress, Detroit, MI, March 2004

3. **Project Presentations**
   AMD Offsite Meeting, October 28, 2004.
   AMD Offsite Meeting, October 27, 2005.