2. AUTOMOTIVE ALUMINUM R&D

A. Active Flexible Binder Control System for Robust Stamping

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

Objective

- Build an advanced closed-loop flexible binder control system for installation in mechanical presses to actively control the sheet metal stamping process.
- Develop computer simulation with process optimization to predict blank holder force trajectories for each cylinder during the press cycle.
- Demonstrate that the system will improve quality, reduce variability, and maintain accuracy of stampings made from aluminum alloys and advanced high-strength steels.
- Demonstrate the economic feasibility of the system by showing that it will reduce time for tryouts and saves money on fine-tuning (welding/grinding), spotting, and setting of production tools.

Approach

- Apply binder control technology to mechanical presses.
- Build a new ten-cylinder flexible binder control unit with a closed-loop control system and pan tooling.
- Retrofit the 26-cylinder Erie flexible binder control unit with a nonlinear control system and liftgate tooling.
- Conduct open-loop control demonstration of the retrofit unit with the GM liftgate.
- 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 ten-cylinder flexible binder system.
- Evaluate technical and economic feasibility of flexible binder technology.

Accomplishments

- Completed retrofitting of the Erie Flexible Binder Control Unit with the appropriate real-time control system to achieve hydraulic pressure control in all of the 26 cylinders in a mechanical press. Retrofitting includes open- and closed-loop simulation studies, hydraulic reconfiguration, integration of dSPACE real-time control system with the binder control unit, electrical reconfiguration, verification of reconfigured electrical and hydraulic systems, and experimental implementation of pressure control for all 26 cylinders.
- Tested the electro-hydraulic/mechatronic system on the Erie Press Flexible Binder Unit and demonstrated closed-loop pressure control in multiple cylinders with different pressure trajectories. These tests were conducted without the binder or die installed.
- Conducted tryouts on the retrofitted Erie unit with the GM liftgate using bake hardenable steel (BH210), dual phase (DP500), and aluminum (A6111-T4). The control system hardware and software performed as desired.
- Successfully stamped BH210 steel liftgate part within about 8 hours of tryout, which included blank alteration, code modification, and conducting tests to determine that the upper was impacting the cushion before the binder. This is compared to an estimated 7 days needed for tryout using conventional methods.
- Built a new ten-cylinder flexible binder control system with special valves and controls for use in a mechanical press and set up for testing at the University of Stuttgart (IFU) in Germany. The associated tooling is based on a die design that included many features of automotive stampings (IFU pan). The unit has a feedback controller with three types of sensors and a touch screen to control pressure profiles in individual cylinders. The unit will be shipped to Detroit for tests and demonstration after functionality tests are completed at IFU.
- Used adaptive simulation and optimization methods, coupled with finite-element method (FEM) simulation, to predict optimum constant and variable blank holder force (BHF) trajectories in single and multicushion systems to reduce thinning and springback in the IFU pan, a fuel tank shield, an S-rail, and a General Motors (GM) rail. Simulation results showed that optimized BHF trajectories can reduce thinning and springback in the analyzed parts. Experiments were conducted to verify the predicted optimum BHF trajectories.
- Variable BHF trajectories improved the formability of conical cup drawing by about 9% compared with constant BHF trajectories. Adaptive simulation results can be used as an initial guess for optimization in reducing the number of iterative simulation runs and computation time.
- Developed procedure for modeling flexible binder in stamping simulation and updated optimization code to predict BHF for multipoint cushion systems.
- Determined that flexible binder simulation resulted in more uniform pressure distribution in the blank, resulting in more thinning and less draw-in and wrinkling compared to rigid binder.
- Established that optimum variable binder force (variable in space, constant in time) resulted in uniform reduction in thinning by 2% to 3%.

Future Direction

- Set up and conduct trials on the new IFU flexible binder control system to determine the benefits of using flexible binder control systems in improving part quality and consistency in automotive stampings.
- Run variable BHF in space and time using the sequential optimization technique for the IFU Pan and GM liftgate.
- Ensure that OEMs and suppliers will check and verify Ohio State University (OSU) results. Develop a mechanism to transfer technology from OSU to project team.
- Use optimized trajectories in stamping tryouts of the IFU pan and the GM liftgate with BH210, DP500, A6111-T4 and A5182-O.
- Determine that due to the difficulty in forming A6111-T4, it appears that finite-element analysis (FEA) simulation results would be critical in determining the required multicylinder BHF trajectories.

- Develop a Graphical User Interface (GUI) to download optimized trajectories obtained from FEA simulations to the real-time control system.

Participants

• Ford Motor Company	Lead project and determine its direction and benefits
• General Motors	Co-lead project and determine its direction and benefits
• DaimlerChrysler	Co-lead project and determine its direction and benefits
• U.S. Steel	Provide steels and technical support
• Rouge Steel	Provide steels and technical support
• ALCOA	Provide aluminum and technical support
• Pathway Technologies	Retrofit binder control unit and install control system
• Ohio State University	Provide simulation and optimization expertise
• University of Stuttgart	Build and ship new flexible binder unit to project
• NIST	Support forming and friction activities
• Troy Design & Manufacturing	Set up tooling and provide equipment for tryouts
• Erie Press Systems	Transfer binder control unit to project
• FormSys	Provide project administration and technical support
• Auto/Steel Partnership	Provide material and technical support

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Introduction

Significant weight saving can be achieved by replacing parts made from mild steel with those made from lightweight materials (aluminum and magnesium alloys) and high specific strength materials (ultra high-strength and stainless steels). Such materials are less formable than mild steel and parts made from them lack dimensional control because of the significant amount of springback that they produce after forming.

Traditional stamping leaves no flexibility in the stamping process for using difficult-to-form materials and for responding to process variations (lubrication, material, die wear, blank placement) that can lead to stamping inconsistencies or even failure. It has been found that failure by wrinkling or tearing is highly dependent on the magnitude and trajectory of the binder force. Recently, dynamic variation of the binder force during the forming stroke has been shown to affect formability, strain distribution and springback. Optimal forming trajectories can be obtained under constant and variable binder force conditions, but there is no guarantee that process variables will remain constant during the stamping process. Specifying a binder force trajectory is not easy because the part shape changes during forming. Also, stresses in the part cannot be determined because the coefficient of friction is not a controllable quantity and it varies from location to location. Therefore, the forming process must be controlled, and a closed-loop system with an appropriate local control parameter (friction, draw-in) must be used to track a predetermined optimum control parameter trajectory.

The project uses flexible binder control technology in conjunction with innovative tool designs and closed-loop control to produce robust processes for stamping aluminum and high-strength steel automotive panels. The focus of this project is to implement binder and closed-loop process control in the stamping industry to increase the robustness of the forming process. This technology will use computer simulation and process optimization to predict optimum binder force trajectories that can be entered into programmable hydraulic cushions to control binder actions in mechanical and hydraulic presses.

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

A two-path approach is adopted to complete this task. The first one is to retrofit the existing Erie Unit with the appropriate real-time control system to achieve hydraulic pressure control in all of the 26 cylinders in a mechanical press environment. The second approach is to have the University of Stuttgart (IFU) build a more robust and smaller unit with only ten cylinders to accommodate a generic tool that captures the main features of industrial stampings.

1. Retrofitting the Erie Unit

Retrofitting the Erie Unit, shown in Figure 1, included the following:

- open and closed-loop simulation studies
- hydraulic reconfiguration,
- integration of the dSPACE real-time system with the binder control unit,
- electrical reconfiguration of the unit,
- verification of reconfigured electrical and hydraulic systems,
- demonstration of pressure control for all 26 cylinders. The unit was used, as previously planned, in conjunction with the liftgate tooling (Figure 2).

Figure 1. Erie binder control unit.

Figure 2. GM liftgate tooling.

Multicylinder Pressure Control Tests

A series of tests were conducted at Troy Design and Manufacturing (TDM) to demonstrate that pressure control can be achieved in multiple cylinders simultaneously using the nonlinear control algorithm developed during the course of this project and validated in single-cylinder tests. The controller parameters were tuned using data from open-loop tests and simulation studies. Low pass filters were digitally implemented to attenuate the sensor noise, and the system achieved stable pressure trajectory tracking (Figure 3).

The figure shows that multicylinder pressure trajectory tracking was achieved by using the nonlinear control algorithm in conjunction with a set of digital filters. The controller was able to deal with flow interaction between the cylinders.

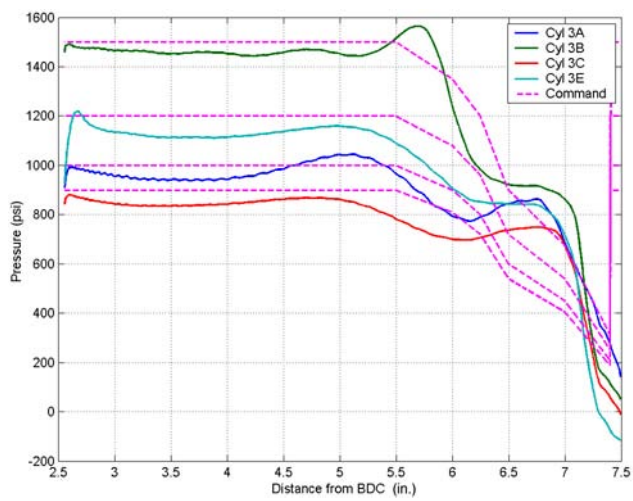

Figure 3. Stable pressure trajectory tracking with digital filtering for multicylinder system.

Tryouts

After achieving multicylinder pressure control with the system hardware and software, tryout tests of the control unit and liftgate die in the press were conducted at TDM. Figure 4 shows the unit and tooling installed in the press.

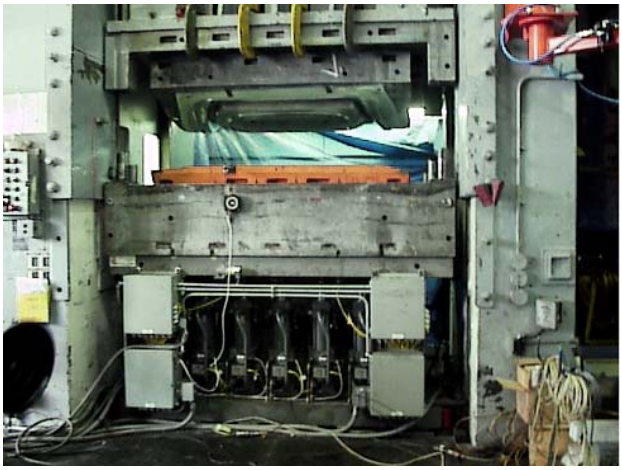

Figure 4. Flexible binder unit in press with tooling installed.

Following a complete system test with the tooling mounted, a number of tryouts were conducted on the GM liftgate using three sheet materials: bake hardenable steel (BH210), dual-phase steel (DP500), and aluminum alloy (A6111-T4).

Results of the tests are summarized:

- The BH part, shown in Figure 5, was successfully stamped within 8 hours of tryout, which included blank alteration, code modification, and conducting tests to determine that the upper was impacting the cushion before the binder. The current tryout period is extremely short compared to an estimated 7 days needed when using conventional tryout methods.
- Stamping of A6111-T4 proved to be difficult. A couple of defects were corrected, but a more structured tryout using finite-element analysis (FEA) simulation results would be required to successfully make the part.

2. Building a New IFU Unit

IFU collaborated with two prominent industrial suppliers in Germany, HYDAC and MOOG, to build the hydraulic and control systems for the binder control unit shown in Figure 6.

The IFU unit has state-of-the-art cylinders, valves, and controls. It accommodates three types of sensors for use in closed-loop control of the binder in a mechanical press environment. The closed-loop control system, shown in Figure 7, will automatically ensure that the desired binder forces are applied to the part by an electro-hydraulic actuation system during the forming process. The system will compensate for minor disturbances in the forming system caused by friction variation, inconsistent material properties, sheet thickness variation, die alignment problems, ram tilt, tool wear, blank placement, and press table deflection.

Feedback measurements are used to modulate the binder force in real-time to keep optimum binder force trajectories for each cylinder in the control

Figure 5. Successfully formed BH210 steel liftgate inner after tonnage adjustment.

Figure 6. IFU flexible binder control unit.

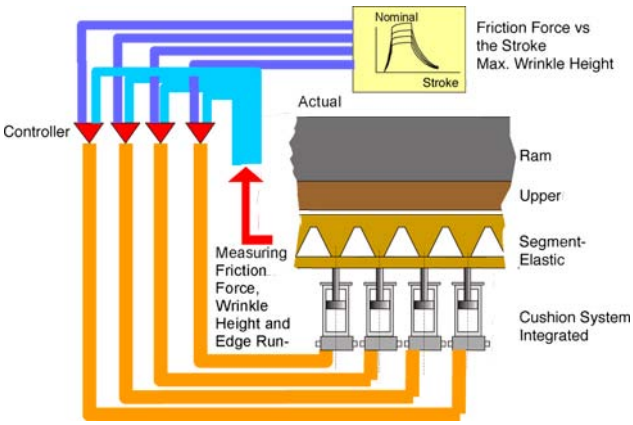

Figure 7. Closed-loop control system.

unit on target. The difference between the input signal and the output response is fed to the controller to reduce the error and bring the output of the process to a desired value. One of the control strategies that can be used would have the following scenario:

- Finite-element method (FEM) produces an optimum material flow/friction trajectory.
- Sensor measures actual material flow/friction.
- Controller manipulates binder to achieve material flow/friction compliance.

Success of the closed-loop control system in the IFU unit will also complete the objectives of Task 4. User interface with the system is accomplished through a touch screen where individual cylinder pressure can be selected.

The IFU unit is equipped and instrumented with a large collection of advanced features: 10 specially designed hydraulic cylinders, 12 proportional valves, 2 encoders for cushion position, 1 encoder for ram position; 4 punch force sensors, 1 wrinkle height sensor, 1 flow in sensor, and 1 friction sensor.

The IFU unit accommodates a generic tool, shown in Figure 8, which captures the main features of industrial stampings.

The test plan at IFU and at the press shop in Stuttgart includes the following:

- Track at least four pressure profiles (constant, ramp-up, ramp-down, and variable).
- Assess characteristics of the friction, draw-in, and wrinkle height sensors.

Figure 8. IFU pan.

- Test the stability of the closed-loop system.
- Optimize pin forces and trajectories for the part.
- Evaluate formed panels (dimensional quality, strain distribution, and surface quality).
- Assess costs to build a flexible binder control system.

The following sheet materials will be tested in Stuttgart and Detroit:

- Aluminum A5182-O, 1.0 mm
- Aluminum A6111-T4, 1.0 mm
- BH210 Steel, 0.8 mm
- DP500, 0.8 mm

After testing the IFU unit in Germany, the following steps are planned:

- Shipment of the die to Detroit. The modified system will be shipped to Detroit only after it has been thoroughly tested in Stuttgart and approved for transportation by a project delegate(s) who will review test results and arrange for shipping the unit to Detroit.
- Setting up and testing the die in the Detroit area in a mechanical press with support of IFU engineers.
- Demonstrate the functionality of the die with open- and closed-loop circuit control. The test plan in Detroit is similar to the test plan in Stuttgart. The experience of the previous tests in Stuttgart will be used for the tests in Detroit.
- Shipment of the die back to Stuttgart, Q205.

Task 2: Develop Computer Simulation and Process Optimization Capabilities for Flexible Binders

The blank holder (BH) applies appropriate restraining force on the sheet metal blank to suppress wrinkles and eliminate splits during forming. Many studies have shown that variable blank holder force (BHF) profiles increase the formability of stamped parts. In this task, Adaptive Simulation (AS) and Optimization (OPT) methods, coupled with FEM simulation, were developed and used to predict optimum, constant and variable BHF trajectories in single and multipoint cushion systems to reduce thinning and springback in the IFU part, the fuel tank shield, the S-rail and the General Motors (GM) structural rail.

Single-point cushions represent the traditional way of applying a constant or variable BHF on a rigid binder. Multipoint cushions represent flexible binders where a variable binder force in space/and or in time is applied to a segmented elastic BH. Differences in modeling the rigid and segmented elastic BH are shown in Figure 9.

Optimization code was updated to determine the BHF that varies in space using the segmented elastic BH for the IFU die. The segmented elastic BH was modeled as an elastic object in the finite-element (FE) simulation of the forming process to account for the deflection of the BH.

The AS technique requires only one simulation run to result in a "feasible" variable BHF profile, whereas the OPT needs many more iterative simulation runs to result in an "optimum" variable BHF profile. In this study, the resultant BHF profile from the AS was applied as an initial guess for the OPT. This resulted in reduced number of iterative simulation runs, which decreased the total computation time.

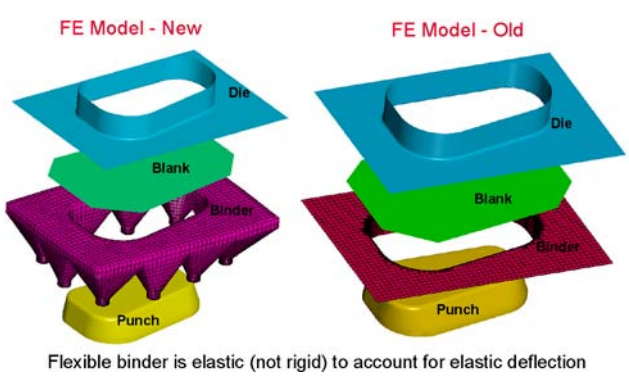

Figure 9. FEM models for rigid (old) and segmented elastic (new) BHs.

Single-Point Cushion Applications

Optimum constant and variable BHF were predicted using OPT and AS techniques for single-point cushion applications on the IFU pan, the fuel tank shield, the S-rail, and the GM structural rail.

Comparison of thinning distribution predicted by FE simulation for 0.92-mm A6111-T4 using three different BHF trajectories obtained from OPT and AS for the S-rail part at a depth of 30 mm is shown in Figure 10.

Figure 10 shows that using variable BHF from AS or OPT results in a decrease in maximum thinning from 34% to about 17% compared to the constant optimum BHF.

Figure 11 shows the BHF predicted by adaptive simulation with and without springback control.

Major conclusions drawn from applying predicted optimum constant and variable BHF using OPT and AS technique for single-point cushion applications on the IFU pan, the fuel tank shield, the S-rail and the GM structural rail are summarized:

- IFU pan—Thinning decreased by 3% for variable BHF from AS compared to optimum constant for materials A5182-O and A6111-T4.
- S-rail—Variable BHF predicted by AS reduced thinning from 34% to 17% compared to optimum constant BF. Springback was reduced ~50% by using variable BHF obtained with

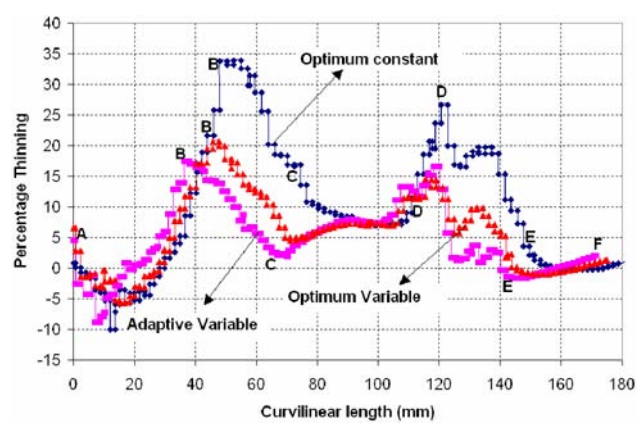

Figure 10. Thinning distribution predicted by AS and OPT for the S-rail.

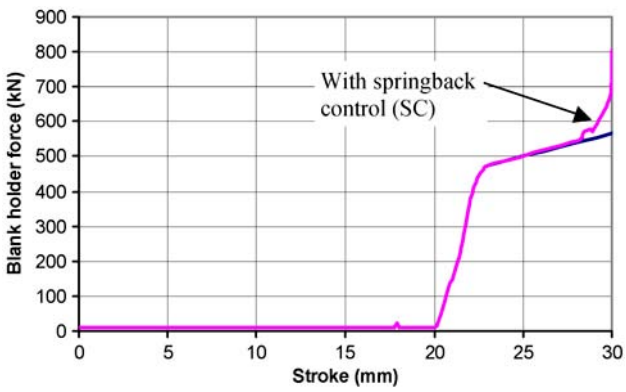

Figure 11. BHF with and without springback control.

springback control compared to variable BHF obtained without springback control.

- Fuel Tank Shield—Thinning decreased from 32% to 30% for variable BHF from AS compared to optimum constant.
- GM Structural Rail—Optimum variable BHF that minimized springback in the part reduced springback by 50% throughout the entire part compared to the variable optimum BHF profile that minimized thinning in the part.

Multipoint Cushion Application

A multipoint cushion system (flexible binder) is used to draw the IFU part. An FE model of the tool is shown in the left side of Figure 9. Materials used for the IFU part are 1.15-mm A5182-O and 1.0-mm-thick A6111-T4.

The IFU flexible binder die has ten independently controlled hydraulic cylinders to apply the BHF during forming. The location of the ten cylinders/cushion pins is shown in Figure 12.

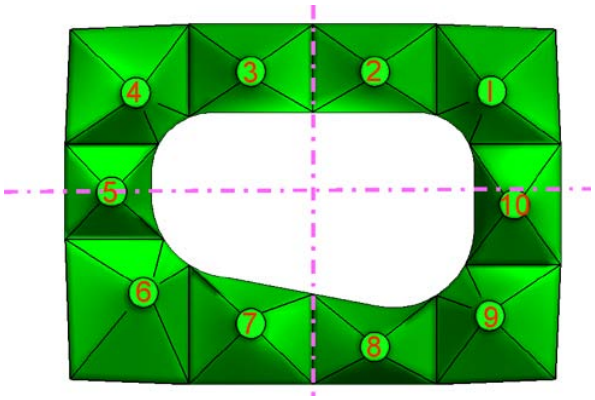

Figure 12. Location of the ten cushion pins in the IFU binder.

IFU pans from A5182-O were drawn to a depth of 75 mm, and those made from A6111-T4 were drawn to a depth of 60 mm to reduce thinning in the part.

Figure 13 shows a comparison between the optimum constant BHF and the optimum variable BHF (in space and constant in stroke) used in FEM simulation to assess thinning in the drawn IFU pan.

Thinning distribution obtained from FE simulations along two sections (Sections XX and YY, Figure 14) were compared for the constant optimum pin force in all the pins and constant optimum for individual pins.

A comparison of thinning distribution obtained for optimum constant pin force (constant in space and time) and optimum constant pin force in individual pins (variable in space and constant time) along section YY for the AA6111-T4 material is shown in Figure 15.

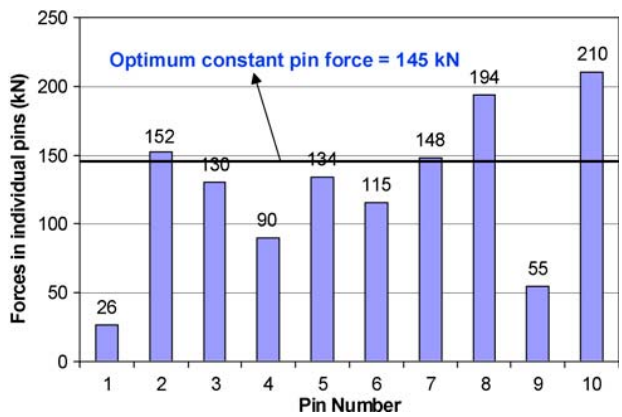

Figure 13. Optimum constant and variable.

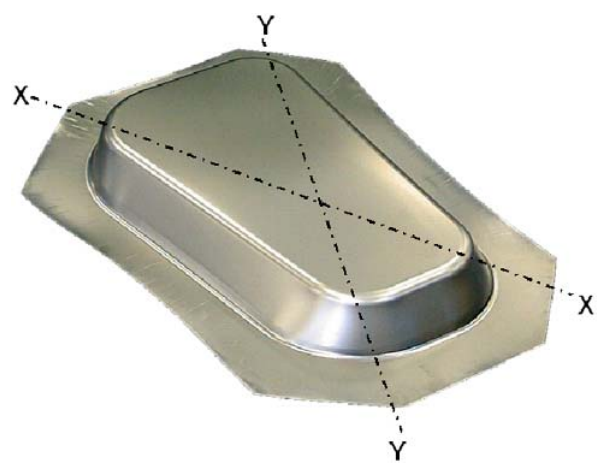

Figure 14. Sections along the IFU part used for thinning distribution comparisons.

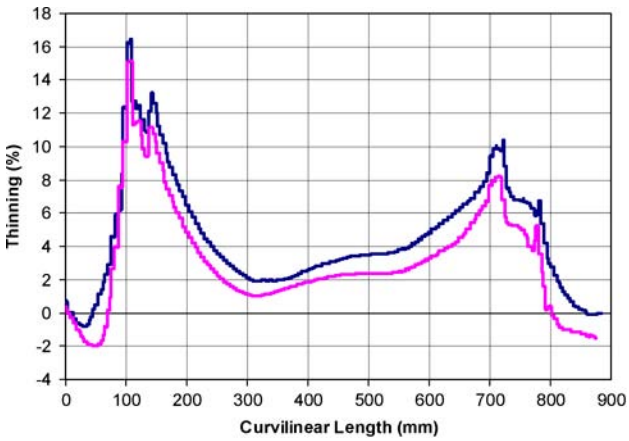

Figure 15. Thinning distributions predicted by FE simulation and optimization along section AA.

Figure 15 shows that by optimizing individual pin forces, maximum thinning in the part was reduced from 17% to 13%, thereby enhancing the drawability of the part.

Major conclusions from the IFU pan flexible binder simulation are summarized:

- Flexible binder resulted in more uniform pressure distribution in the blank, resulting in more thinning and less draw-in and wrinkling compared to the rigid binder.
- Flexible binder deforms elastically during forming simulation and remains in uniform contact with the nonuniform sheet thickness, thereby producing uniform contact pressure due to the applied BHF. Rigid binder, however, is in contact with the sheet at relatively thicker locations, thereby exerting a nonuniform pressure distribution due to the applied BHF.
- Thinning reductions from 17% to 13% were obtained by varying the forces in each pin (BHF varying in space and constant time) compared to the constant force in all the pins (BHF constant in time and space) for parts drawn from A6111-T4 to a depth of 60 mm. Reductions from 21% to 16% were observed for parts drawn from AA5182-O to a depth of 75 mm.

Summary

Highlights of the progress during FY 2004 follow:

- Retrofitted the 26-cylinder Erie Binder Control Unit by fixing its open-loop control and hydraulic problems. The Unit was successfully used in tryouts at TDM, and the control system hardware and software were shown to perform as desired.
- Built a new ten-cylinder IFU Binder Control Unit with closed-loop control and pan tooling.
- The electro-hydraulic/mechatronic system on the retrofitted Erie Press Flexible Binder Unit was tested, and closed-loop pressure control was demonstrated in multiple cylinders with different pressure trajectories. These tests were conducted without the binder or die installed.
- The system was tested with tooling installed, and synchronization algorithms to raise (and lower) the binder and inner cushion were validated as part of the control strategy.
- Actual tryouts for a liftgate inner were conducted with the unit using steel (BH210 and DP500) and aluminum A6111-T4.
- The steel (BH210) part was successfully made within about 8 hours of tryout (blank alteration, code modification, and conducting tests to determine that the upper was impacting the cushion before the binder) as compared to an estimated 7 days using conventional tryout methods.
- Initial attempts at stamping DP500 and A6111 proved to be difficult. A couple of defects were corrected, but a more structured tryout using FEA simulation results would be required to successfully make the parts.
- A few final mechanical modifications and hydraulic repairs need to be made before proceeding with tryout using A6111 and DP500.
- Current work involves addressing the mechanical issues, repairing and installing the missing cylinder, and designing a GUI to download trajectories obtained from FEA simulations to the real-time control system.
- AS and OPT programs to predict optimum constant and variable BHF profiles have been developed and successfully implemented on many parts (cylindrical cup, rectangular pan, IFU pan, S-rail, fuel tank shield, and structural rail).
- Procedure for modeling flexible binder in stamping simulation has been developed.
- OPT code was updated to predict BHF for multipoint cushions.
- Flexible binder resulted in more uniform pressure distribution in the blank, resulting in

more thinning and less draw-in and wrinkling compared to rigid binder.

- Optimum variable binder force (space) resulted in uniform reduction in thinning by 2% to 3%.

Conclusions

After facing some technical and organizational hurdles, retrofitting of the Erie Binder Control unit is now complete. The unit was successfully used in tryouts at TDM to stamp the GM liftgate. Also, similar delays were experienced during design and build of the IFU flexible binder control unit. The unit has finally been built. Its functionality is being evaluated in Germany before shipment to Detroit for testing and demonstration. The simulation and optimization task has proceeded according to plan. Three of the four major milestones are essentially satisfied.

Presentations and Publications

1. H. Palaniswamy, A. Thandapani, S. Kulukuru, and T. Altan, "Prediction of Blank Holder Force in Stamping Using Finite Element Analysis," presented at UNIFORM Conference, Columbus, Ohio, and presentation and publication at the SAE Congress, Detroit, Michigan, March 2004.
2. C. Du, J. Wu, M. Militisky, J. Principe, M. Garnett, and L. Zhang, "Springback Control With Variable Binder Force—Experiments and FEA Simulation," presented at the SAE meeting, Detroit, Michigan, and presentation and publication at the Numiform Meeting, Columbus, Ohio, May 2004.