C. Die Face Engineering Project for Advanced Sheet Metal Forming

Principal Investigator: Dr. Chung-Yeh Sa
General Motors Corporation
MC 480-111-S60
30200 Mound Road
Warren, MI 48090-9010
Phone: 586-947-0660, Fax: 586-986-8722, e-mail: chung-yeh.sa@gm.com

Principal Investigator: Laurent Chappuis
Ford Motor Company
VOGO - Advanced Stamping Engineering
17000 Oakwood Boulevard
Allen Park, MI 48101
Phone: 313-322-4470, Fax: 313-322-4359, e-mail: lchappui@ford.com

Principal Investigator: Li Zhang
DaimlerChrysler Corporation
CIMS 482-60-05
800 Chrysler Drive
Auburn Hills, MI 48326
Phone: 248-576-3117, Fax: 248-576-2230, e-mail: lz@daimlerchrysler.com

Project Administrator: Manish Mehta
TRC-National Center for Manufacturing Sciences
3025 Boardwalk
Ann Arbor, MI 48108-3266
Phone: 734-995-4938; Fax: 734-995-1150; e-mail: manishm@ncms.org

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Objective

The ultimate project goal of the 3-year AMD 408 Die Face Engineering Project (DFEP) is to develop robust technology to improve die design and die processing so as to reduce manufacturing costs for all sheet metal parts using lightweight materials, by generating optimized sheet stamping dies from CAD surfaces (from FEM mesh) that compensate for springback while maintaining formability, eliminating the soft tool prototyping phase, and reducing die tryout phase.

The project deliverables include: (1) Integrated product-process finite element analysis capability that will more accurately predict springback for both closures (>90%) and structural parts (~80%); (2) Test results from simulations, panel trials and springback measurements that will be used to guide and validate the software development (done at private expense by vendors); and 3) Capability to automatically and consistently generate a machinable CAD surface of acceptable quality from FEM mesh.

Approach

The DFEP approach is to develop and validate improved simulation technology that provides more accurate and reliable springback predictions encountered in automotive sheet stamping operations.

The collaborating partners include Alcoa, DaimlerChrysler Corporation, Ford Motor Company/Volvo Cars Division, General Motors Corporation, ThyssenKrupp Budd Company, US Steel, Livermore Software Technology Corporation (LSTC), and Technologies Research Corporation of the National Center for Manufacturing Sciences (TRC-NCMS). The project tasks are being undertaken and reported in four main task areas:

A. Numerical Technology
B. Material Testing/Modeling
C. Field Validation
D. Surface Technology

- The DFEP approach has been to work with technology vendors and test laboratories to significantly improve the ability to: (a) analytically predict springback more accurately and validate for a broader range of closure and structural parts and (b) recommend optimized tool geometry (FEA mesh to CAD surface) so as to produce panels with the desired final shape after springback. The project will utilize results of the Springback Predictability NIST Project (1995-2000) incorporated in LS-DYNA, a commercial software from LSTC, and the USAMP Springback Compensation Project (SCP) AMD 311(2003).
- In Year 1, the DFEP team began to identify and classify part categories for which springback is still a challenge to predict (e.g., underbody parts), then conduct new simulations utilizing significant LS-DYNA improvements (developed at vendor expense and owned by vendor) and its linked modules to input original tool geometry, incorporate new material and process parameters, identify design variables, perform springback simulations, and output optimized tool geometry with material and process parameters.
- Springback predictions will be validated against dimensional measurement data obtained from tryout experiments with a “common” experimental die (incorporating challenging features for forming baseline panels of an underbody structural part in Year 1 and a trim die in Year 2) used to produce both aluminum and advanced high strength steel body panels with representative features.
- Finally, in Year 3, an integrated product design-analysis-formability capability will be demonstrated that combines improved springback simulation algorithms (material and surface contact) defined by the team and CAD-based die-face modification algorithms, which will be applied to the common die component. A new die surface will be generated for tryout and a second set of structural panels formed and measured to validate the prediction technology.
- A larger internal validation effort will be undertaken in Year 3 by the OEMs to industrialize “best practices” simulation standards and extend the integrated springback and CAD morphing technology to test additional challenging automotive parts.
- A technical cost model will be developed, comparing cost, quality and user-effort attributes of the improved simulation and tool development capability with the conventional (baseline) die build and tryout process.

Accomplishments

Reported under each Project Task Area:

Numerical Technology:

- DFEP Team conducted simulation experiments on an initial set of closure and structural parts to classify springback behavior, based on several end-user defined computational and prediction quality parameters. A consensus Springback Classification Table was developed.

- Developed smooth contact algorithms for improving geometric description of the products and springback predictive accuracy in FEM.
- Developed a new element with improved through-thickness stress variations that will help improve springback prediction.
- Conducted several detailed benchmark studies to understand the impact of various numerical technologies and define directions for further code improvements by the software vendor.

Material Testing/Modeling:

- Conducted literature review and performed baseline simulations of NUMISHEET benchmark parts and other simple geometries (e.g., Deep Draw Cup) to define critical material parameters, testing needs and modeling requirements for steel and aluminum sheet alloys. These models and measured parameters/coefficients will help drive the needed code improvements and accuracy in springback simulations. Material test data requirements include: tension and shear testing, stress-strain, tension-compression testing, and bending-unbending testing.
- Evaluated candidate test methods from team members and lab vendors, and contracted material testing to two selected laboratories to perform testing and validation of existing material models.
- Began implementing new material models into predictive code, such as non-linear isotropic and kinematic hardening models.

Field Validation:

- Designed and sourced pre-production stamping tooling for a “Common Die” structural automotive part geometry (previously defined in FY 2004) exhibiting challenging formability and springback behavior, for test and validation of incremental enhancements of new (privately developed) FEM software.
- Conducted baseline simulation experiments on the Common Die to predict formability and springback for high-strength steel sheets of DP 600, and DP 780 alloys, and aluminum 5754-O alloy.
- Completed all design modifications, draw die development, construction and tryout of the Common Die for the first phase of panel trials, which included 36 stamped panels of selected dual-phase steel and aluminum sheets.
- Conducted panel grid and strain measurement study on selected full- and half-size panels, using new global surface strain measurement technology.

Surface Technology:

- Developed and evaluated surface morphing criteria for facilitating efficient and accurate die development and modifications. This is an enabling technology for reduced lead times and labor in translating CAE designs/analyses to machinable CAD and NC programs.
- Evaluated current commercial CAD packages and established a baseline capability of CAD morphing performance, quality and computational goals for use in a FEM die design environment. Defined technology and performance gaps needed for improvement.
- Demonstrated and validated mesh-to-surface and surface-to-surface mapping algorithms with the same element topology.

Future Direction

- Expand the springback simulation and classification study to additional team-defined structural and closure components, and characterize springback behavior based on simulations and product measurements.
- Demonstrate feasibility of using enhanced springback prediction code with improved contact algorithms for various forming processes.

- Define technical and quality specification for achieving morphed CAD surfaces from FEM meshes of modified dies.
- Select CAD software vendors to partner with in demonstrating new mesh-to-CAD capability in die face engineering.

Introduction

Excellent progress was made in each of the Die Face Engineering Project (DFEP) focus areas described below in greater detail. The DFEP project has achieved two major technology improvements in simulation technology during the first year of the project, demonstrating results that are independent of input parameters. The first accomplishment is that the predicted springback results have been significantly improved using several new algorithms (vendor-owned) implemented in the project. Secondly, the predictive accuracy of the LS-DYNA FEM code has generally improved from 80% to over 90% in several product cases tested – code improvements to improve the consistency and reliability continue so that these predictive accuracies apply to a broader range of structural and closure panels and sheet materials. These advances have major implications to our goals to eliminate the soft tool trial, and reduction of lead time and cost for tryout of hard tools (up to 50%), and thus can help accelerate the application of advanced lightweight metals. Design refinements and baseline forming/springback simulations of a "Common Die" component were conducted early in Year 1. A capable die vendor was selected and contracted to source the insertable Common Die that has embedded difficult-to-predict springback features. The die tryouts on dual phase steel and aluminum panels were witnessed by DOE sponsors during the last quarter of Year 1.

Discussions were held with the Auto-Steel Partnership (A/SP) project team working on "High-Strength Steel Stamping and Springback Prediction Project" (see report 2.R). The A/SP project goal is to achieve springback control using process changes and modifications. The DFEP Team has formally involved A/SP project leadership, in order to exchange and leverage technical information.

Numerical Code Development:

- <u>Springback Classification Study:</u> The OEM members of the DFEP Team collaborated to conduct a study of springback behavior for a wide variety of production parts, based on measured springback data. These parts included rails, sills, pillars, etc.
- <u>Surface Algorithms:</u> The DFEP Team worked with FEM vendor LSTC to help develop and improve new surface algorithms for forming and springback predictions. The DFEP Team conducted validation studies on three production panels, one from each OEM. The feasibility demonstration of surface-based simulation capability for forming and springback prediction (a stretch target of the DFEP with high technical risk, and potential for high impact on project goals) were re-directed to a more efficient approach by using smooth contact algorithms.
- <u>Smooth Contact Algorithms:</u> Based on DFEP Team input, LSTC developed smooth contact algorithms aimed at improving the geometric description of the products and. therefore, springback predictive accuracy. The effect of the number of elements on the tooling radius was studied (# of elements ranged from 1 – 10). It was found that using the new mesh adaptivity feature, the number of elements in the corner of rigid tools now has a much smaller effect on the springback prediction results. Other studies have involved using three different contact scale factors (SLSFAC) combined with initial coarse mesh, initial coarse mesh with smooth contact, and initial fine mesh with smooth contact.
- <u>Higher Order Element:</u> LSTC also developed and implemented a higher-order element with improved through-thickness stress variations. The springback characteristics being studied include twisting, warping and out-of-plane bending, and are applicable to various forming processes (e.g., draw, trim and flanging).
- <u>Benchmark Study:</u> The DFEP Team and LSTC have jointly performed detailed simulation studies on benchmark components (e.g., Deep Draw Cup, NUMISHEET '93 U-channel – see Figure 1) to better understand the impact of various numerical technologies on computational efficiency and prediction

accuracy. Three different sheet materials and two different binder forces have been used. In Year 2, the Team will test these new features on real production panels.

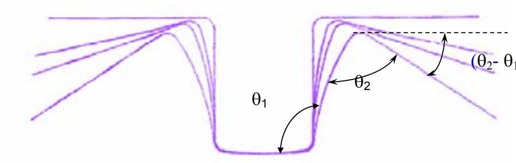

Figure 1. The NUMISHEET '93 U-channel Benchmark Showing Springback Predictions for Three Simulation Cases.

Material Testing/Modeling

- The motivation for undertaking this task was that currently available public domain material models do not seem to reflect the processing realities when sheet metal undergoes multiple bending-unbending cycles typical of a sheet forming operation. In order to assess the many theoretical models, a literature review of feasible material models was performed during the year, which helped in identifying candidate material models for further customization and characterization with input property and parameter measurements. This activity resulted in a gap analysis and model development roadmap to drive the property measurement tasks to validate existing models and subsequently implement into new FEM code. Candidate models included nonlinear isotropic and kinematic hardening. Highlights of the literature review were presented at the Team Offsite in December 2004, and disseminated to our NIST collaborators.
- Volvo's shear test method (Figure 2) was used to extend mechanical stress-strain behavior of the candidate DP 600 and aluminum 5742 alloys to levels beyond the conventional tensile test method. This method is particularly well suited for metals exhibiting small uniform elongations. Volvo is using the shear test to obtain the data at large strain levels, and apply the measurements for simulating the Common Die forming operations and springback.
- Additional test methods and capable vendors were identified for material testing and model fitting to develop a combined isotropic kinematic hardening model that (when implemented into numerical code) can improve springback predictions. These include the Fraunhofer tension-compression test method that can better characterize cyclic loading characteristics of material behavior that can be fit to the Chaboche material model. This method will impose material strain levels up to 15%.

Figure 2. Volvo's Large-Strain Shear Test Setup for Common Die Sheet Material.

Surface Development

- The primary goal of the Surface development task is to assist the CAE/Stamping Development engineer to quickly translate CAE die design (or modification information) directly into CAD data that can be used in machining dies.
- The Surface Team began in Year 1 by evaluating and developing an OEM-led, consensus set of morphing criteria for die development and modification. This first involved developing a collective understanding of how parametric design data is rendered into machinable CAD-quality surfaces. A CAD-NC tooling specialist from DaimlerChrysler facilitated this activity.

- The second major achievement was to conduct evaluations of current commercial CAD packages, and to establish baseline morphing capability. Three CAD vendors (whose products are compatible with a FEM design environment) were contracted to perform trial morphing on OEM-supplied component product data and target FEM meshes, ETA, D2M-Think3 and ICEM. Each OEM provided two CAD product data sets, a baseline FEM mesh and a modified (target) FEM mesh. Two example product geometries provided by the OEMs are shown in Figure 3. Evaluations performed by the CAD vendors included mesh-to-surface and surface-to-surface mapping algorithms with the same element topology. Final results remain to be evaluated, based on which a down-selection of vendors will be made to pursue new morphing technology developments in Year 2.

Field Validation

- A capable die vendor, Superior Cam, was selected by team consensus and contracted to source the insertable Common Die that has embedded difficult-to-predict springback features. The die enables the DFEP team to completely validate the springback predictability of certain key improvements in numerical codes and evaluate FEM technology implementations. The intent is to use this platform to build stamping dies "right the first time".
- Collaborative design refinements and baseline forming/springback simulations of a "Common Die" component were conducted early in Year 1 – the part geometry is shown in Figure 4. Existing (baseline commercial version) LS-DYNA code was used to generate baseline springback predictability at critical measurement locations.

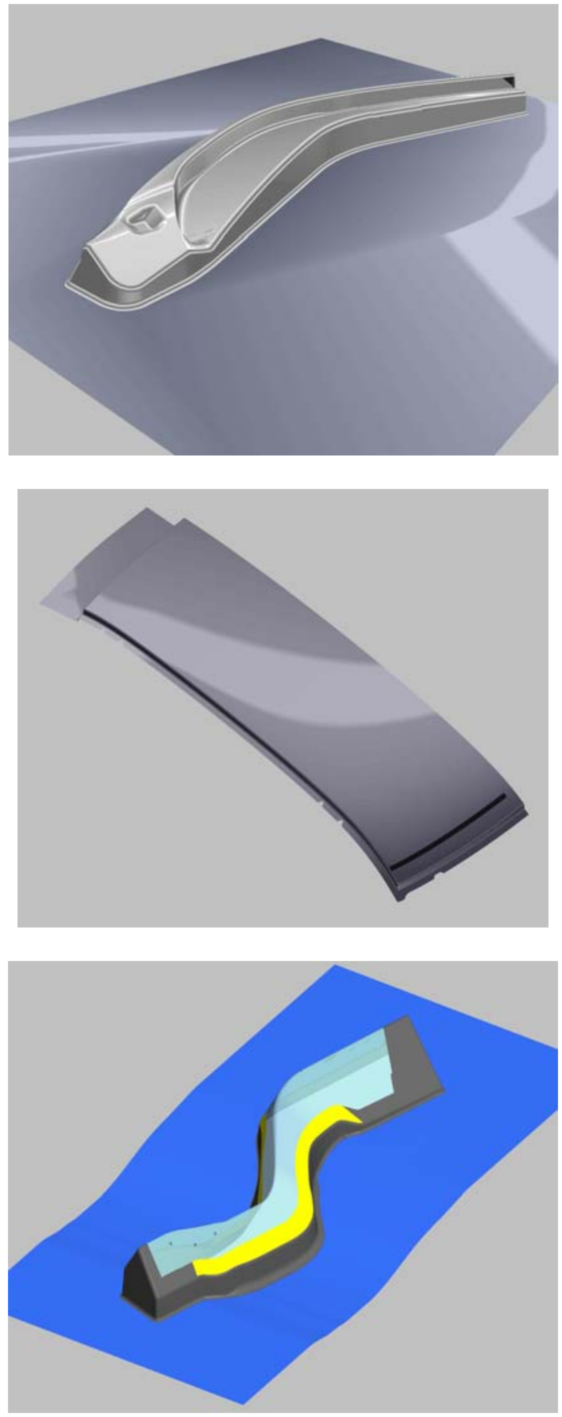

Figure 3. Example OEM Part Geometries Used in Conducting CAD Morphing Trials.

Figure 4. Illustration of Common Die Panel, Indicating Datum Points (Shown in Red).

- The preliminary forming (for die tuning) and die tryouts on dual phase steel and aluminum panels were held at American Tooling Corp. (ATC), and witnessed by DOE sponsors (Dr. Joe Carpenter and Rogelio Sullivan) during the last quarter of Year 1. The Team also attempted several forming trials on DP 780 sheet, which is a very challenging material to form due to its high stiffness; initial trials resulted in split panels. This effort is extra, and goes beyond the scope of the DFEP.
- During the last quarter, a total of 36 panels were formed at ATC for further study and specialized measurements, which included 9 gridded panels (for use with Auto-Grid technology for determining full-field-of-view surface strains), as shown in Figures 5 and 6. Sixteen aluminum 5754-O, 16 DP 600 steel and 4 DP 780 steel panels were stamped (16 full-sized and 20 half-sized panels). During the next quarter (FY 2006), the plan is to complete strain reading of all panels, scanning of all draw panels, and then to laser trim selected panels. All cases will have accompanying forming and simulation predictions, which will be compared with panel measurements, and then developed into validation metrics and guidance to the numerical code development task.

Figure 5. Tool-Shop Showing All DFEP Baseline Formed Panels Using the Common Die.

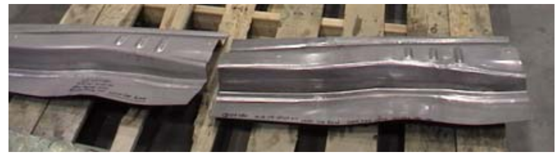

Figure 6. Close-up of a Half-Sized DP Steel Baseline Panel Formed on the Common Die.

Contributions of NIST

NIST Metallurgy Division (using internal laboratory funding) has also contributed by addressing certain fundamental science needs of the DFEP Material Testing/Modeling tasks that aim to improve the quality and precision of data. These contributions were in the following areas:

- Springback Deep-Draw Cup Test – to develop a standard test for evaluating the springback behavior of aluminum and steel alloy sheet.
- Surface Roughness/Friction – NIST began studies to a) accurately assess the relationships between surface roughening in the sheet and the friction that occurs during multi-axial deformation and b) improve the materials property data and constitutive equations to account for the variability exhibited in friction produced in the forming process.
- In-situ Multi-axial Stress Strain - Direct *in situ* measurement of multi-axial stress/strain of steel and Al sheet undergoing deformation using non-proportional loading paths.
- Small-Scale Tension/Compression Test - NIST is developing a test protocol to evaluate the work hardening behavior of a thin sheet during compression/tension cycles. Standardization through ASTM and ISO will be pursued.