2. AUTOMOTIVE METALS

A. Warm Forming of Aluminum II

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Objective

This project previously demonstrated the potential of warm-forming (WF) technology to significantly improve the formability of aluminum. The Phase I demonstration was done in “prototype” mode and demonstrated the expanded depth of draw that is possible with WF. The objective of Phase II is to:

- Develop and demonstrate a production process for the WF of aluminum for automotive body structures and measure the economic feasibility of the WF process for a production environment.

Approach

- Develop individual elements of the WF process in a laboratory environment including alloy characterization, lubricant development, forming simulation and process thermal modeling.
- Develop full-size demonstration of WF process and run tests in a production-like environment. Process will include blank preheating, lubricant application, WF press and die with modified thermal profile controls, and lubricant removal.
- Create a technical cost model that can generate cost comparisons between a warm-formed aluminum door inner and a same or similar door inner manufactured using conventional forming processes in steel and aluminum.

Significant improvements in the formability of aluminum are expected to be achieved through development of enabling WF process advancements including:

- Establishing the degree of improvement in formability of production-grade, commercial aluminum alloys.
- Developing a cleanable lubricant suitable for use in a WF process.
- Optimizing the temperature distribution of the die for improved thermal control and formability.
- Evaluating rapid preheating systems for blanks.
- Applying CAE simulation tools (finite element analysis) to modify the die to attain a production-quality part.
- Optimizing a process and layout design.
- Applying the results of the cost model to optimize process design.

To demonstrate the manufacturing and economic feasibility for a new production process such as the WF process, the definition of the process flow is paramount, as well as the development and application of a technical cost model that allows comparison of a product made in the WF process with a comparable component fabricated from aluminum or steel using current stamping technology.

Accomplishments

Achievements toward these goals through FY 2005 included the following:

- Completed aluminum alloy characterization and laboratory-based WF process studies, including aluminum-alloy sheet fabricated from custom-ormulated 5000 series alloys and commercial alloys 5182-O, 5182-H18, 5754-O and 5754-H18.
- Determined constitutive equation for AA5182 for formability simulation.
- Determined scheme for most uniform heating of die by adding new or relocating heaters, changing setpoints, wattage, and insulation/isolation.
- Completed die refurbishment based on forming simulation and prepared it for use in production demonstration.
- Identified a suitable lubricant through extensive laboratory-based studies. Lubricant application trials conducted and lubricant applied for WF trials.
- Developed a method for blank heating which would enable cycle times of 6-10 jobs/minute. However, the budget, established in 2001, did not allow for full-scale preheater and material handling automation design/build. It was decided that the demonstration would use an available OEM oven to preheat the blanks for the demonstration trials and the blanks would be moved manually, thereby allowing the project to remain within budget.

Future Direction

- Set up and conduct production demonstration – November 2005
- Evaluate the post-formed mechanical properties of the warm-formed parts – January 2006
- Employ the technical cost model to compare costs of WF and alternative processes.
- Create Mg sheet program – Sept 2006.

Introduction

The need to improve fuel economy has led automakers to explore lightweight materials such as aluminum for automobile body and closures. While attractive from a mass perspective, there are many challenges to the widespread use of aluminum including:

- Limited formability compared to steel
- Sliver management in trimming aluminum panels
- Appearance problems in most 5000-series aluminum panels

Phase II of the Warm Forming of Aluminum project was initiated after the initial technical feasibility of forming complex shapes at elevated temperatures was previously demonstrated in Phase I. It is a four-year development and demonstration program to establish the "production" feasibility of warm-forming aluminum-alloy blanks into automotive panels and to fully demonstrate a warm-forming process for cost-effectively manufacturing aluminum automotive panels that require a deep drawn shape. See Figure 1.

This project focuses on the following objectives:

- Developing and demonstrating a warm-forming process including the materials, equipment, and heating processes that can cost-effectively expand the forming limits of aluminum sheet.

Figure 1. Warm-formed door inner from Phase I showing deep-drawn shape yielded by the Phase I die.

- Developing a technical cost model for the warm-forming process to evaluate the economic feasibility of the warm-forming process specific to component design.

The key enabling process improvements to make warm forming a production-capable process are the following:

- A high-temperature lubricant with good lubricity at warming-orming conditions, that is easy to clean prior to automotive painting.
- Temperature distribution management on the die surface during the forming operation.
- Identifying an effective preheating method for blanks.
- Identifying an optimum alloy for warm forming and characterizing its mechanical behavior at elevated temperatures.

Phase II Detail

Technical Cost Model: Technical cost model is complete. Camanoe Associates developed a detailed cost model based on a process sequence defined by the project team. Through use of the cost model, it was identified that aluminum-alloy cost accounted for over 70% of the cost of the end product and hence project research was refocused on commercially available alloys rather than "new" alloys with exotic alloying additives. Preliminary technical cost feasibility is positive and will be verified following the demonstration trials. Additionally, the model will be adjusted based on knowledge gained from the demonstration run. The cost model will allow warm forming of aluminum to be compared to conventional steel stamping and multi-piece assembly as a function of volume.

Alloy Selection: The University of Michigan completed analyses of the warm formability of commercial aluminum alloys and identified parameters affecting the sheet fabrication process for warm-forming-capable aluminum sheet.

Lubricant Selection: The performance of selected lubricants under various temperature, travel time, and load pressures was evaluated at the University of Michigan in collaboration with GM and Fuchs' Lubricants. Additionally, friction tests were conducted at Ford using pre-lubricated coupons to establish optimum lube type and thickness to temperature relationships.

Die Thermal Analyses: University of Michigan's S. Wu Manufacturing Center performed initial Finite Element Analyses of temperature profiles on the warm-forming tooling for Neon Door Inners built in Phase I. Die geometry and heater location data were obtained from CAD models created in Phase I provided by Sekely Industries. See Figure 2.

In 2005, further thermal analyses were completed at GM using proprietary thermal analysis software. These analyses contributed to the final thermal distribution scheme for achieving the most uniform heating of the die by adding new or relocating existing heaters, changing setpoints, wattage, and insulation/isolation. Setpoints on the die and ring were determined for various thermal conditions ranging from 150°C to 350°C.

Blank Heating: Evaluations of infra-red heating and conduction heating methodologies for heating laboratory-scale blanks were investigated at The University of Michigan and Ford Motor Company, respectively. The results assisted the team in identifying the preferred heating methodology for blank pre-heating for a WF production process.

Alloy Fabrication: Pechiney Rolled Products-Alcan supplied the special formulation 5000 series and commercial AA5182 aluminum sheet for these formability studies. Magnesium Elektron (formerly Spectrulite) supplied commercial-grade magnesium sheet for the WF feasibility trials.

Figure 2. Picture of the warm-forming die constructed for the feasibility demonstration performed in Phase I.

Full-scale Process Demonstration: With the individual component processes validated at laboratory level for technical and economic process feasibility, the full-scale warm-forming demonstration using modified door inner stamping dies from Phase I will be conducted starting in November 2005. The process demonstration will be conducted in the local Detroit area allowing direct participation of the OEM team.

Post process inspection and material analyses: Coupons from warm-formed parts will be cut out and the materials properties will be evaluated by the OEMs. The typical properties to be evaluated will include strength, distortion, corrosion, cleanability, etc.

Phase II 2005 Accomplishments

Forming Simulation

FEA simulation was applied to WF die to understand forming process and guide die modification process. A CAD model was created of WF die by scanning in hot and cold state (NVision 3D and 3D Scan). Simulations were performed with various binder configurations (gaps) and coefficients of friction to find upper and lower bounds on final thickness prediction.

Simulation results will be correlated with experiment during post-form analysis of warm-formed panels.

Alloy and Formability Analysis - Pechiney (Alcan)/GM

GM and their subcontractor, MSU, completed the development of a constitutive equation for AA5182 supplied by Pechiney-Alcan for formability simulations done at Ford. Subsequently, the constitutive equation was provided to the WF OEM team. See Figure 3.

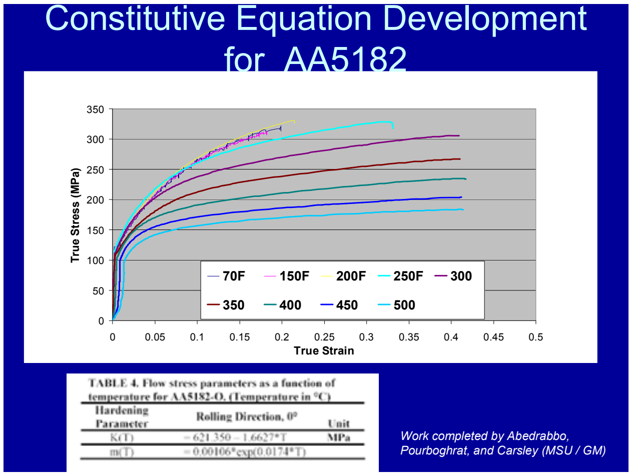

Figure 3. Constitutive equation for AA5182 for use in formability simulations.

Lubricant/Lubrication System

A production-viable, warm-forming lubricant and production-capable method of applying the lubricant was identified and implemented at a subcontractor to GM, Jay & Kay Manufacturing. Lubricant application trials were completed at Jay & Kay Manufacturing in August 2005. Additional laboratory friction screening was completed at Ford to test lubricity. Lubricant was applied for warm-forming trials scheduled for October-November 2005.

Thermal Analysis of Dies

A scheme for the most uniform heating of the die was determined involving the addition of new heaters, relocation, and removal of heaters, as well as changing setpoints, wattage, and installing new insulation for thermal isolation. Preliminary analysis was completed at GM using proprietary thermal analysis software in June 2005. See Figures 4 and 5. These thermal analyses resulted in being able to recommend new heaters and locations. Additionally, setpoints were determined for various thermal conditions for the die and ring ranging from 150°C to 350°C.

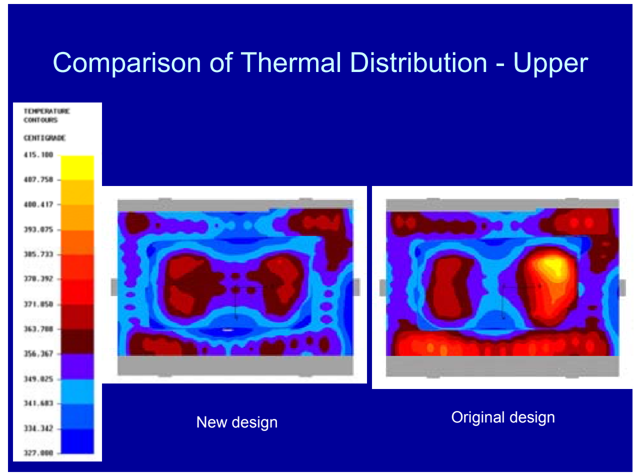

Figure 4. Thermal analyses before and after upper die design changes.

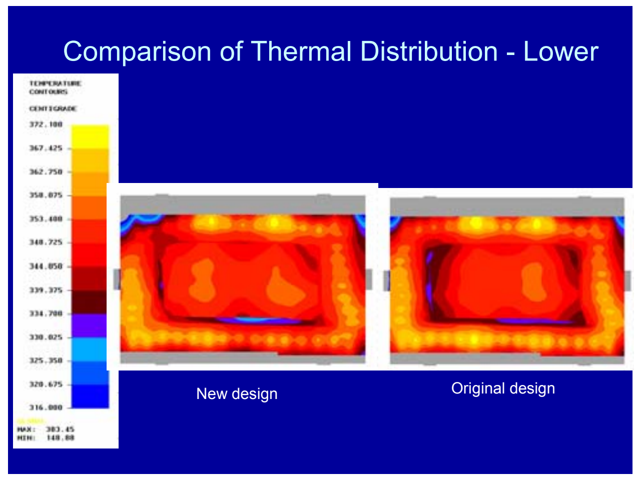

Figure 5. Thermal analyses before and after lower die design changes

Modification of WF Die

The forming die and heating system was modified to improve part quality during 2005. The modifications included:

- Machining of cavity walls to remove tight spots.
- Machining rings to modify drawbeads.
- Modify heaters in punch based on results of thermal CAE studies.
- Addition of heaters in the corner of the punch and cavity.
- Refurbish heater controls.
- Add fasteners to hold down cavity, upper and lower rings.

Blank Heating System

In February 2005 it was determined that the project budget was insufficient to fund the design and building of a full-scale, blank-heating and material-handling automation system as evaluated in the laboratory trials performed at UM, GM and Ford. The laboratory evaluations of a conduction system would enable cycle times of 6-10 jobs/minute, and could be implemented by any of the OEMs for production applications. It was ultimately decided that the preheating and blank transfer system was not so unique so as to require the allocation of additional R&D budget in Phase II. Additionally, sufficient information exists from Phase II laboratory trials and supplier quotations to allow cost and cycle time data to be included in the technical process cost model. Therefore, it was decided that a GM oven (Figure 6.) would be used for blank preheating and blanks will be manually transferred between the oven and die during the demonstration trials.

Alloy Sheet Fabrication

Previously, the decision to use commercially-available material eliminated the need for further research to develop costly special alloys. In 2005, AA5182 was supplied by Pechiney – Alcan for the demonstration trials. Additionally, magnesium sheet for initial feasibility runs was purchased from Magnesium Elektron (MEL).

Figure 6. Picture of blank heating oven that will be used during warm-forming demonstration trials.

Process Demonstration

Substantial progress was made during 2005 to incorporate the various elements of WF process developed in this Phase II into a full-scale process demonstration. The demonstration was re-scoped and re-timed in February 2005 with the approval of the board of the USAMP's Automotive Metals Division (AMD). Significant steps made toward process scale-up included the selection of Troy Tooling Technologies as the source for die and controls rebuilding, press and hot-die fit-up, and demonstration trial implementation.

Demonstration trials are to include:

- Refurbished and thermally-optimized die
- Improved panel quality
- Hot machining
- New lubricant with production application
- Blank preheating with GM oven
- No extraction automation
- Include Mg blanks

Trials are set for November 2005.

Summary and Conclusions

Alloy Selection: 5182-O Al alloy has sufficient attributes for warm forming to support its use in the scale-up demonstration phase. Findings from the alloy characterization studies pertinent to the scale-up demonstration phase include the following:

- Full-hard 5182 aluminum has observable rolling-induced damage, which is absent in 5182-O.
- Full-hard 5182 alloy can be recrystallized by rapid heating; formability remains worse than 5182-O sheet.
- 5182-O alloy shows an improved cup height of 20 mm at 350°C as compared to room-temperature tests.
- 5182-O alloy has a biaxial forming limit of 40% x 40% (approximately) at 350°C.

In the demonstration phase, Mg sheet will be tested using the warm-forming demonstration process and tooling to empirically evaluate the result. Mg behavior and blank-forming results will help the

OEMs determine what developmental work may be required to warm form Mg.

Blank Preheating and Forming Studies: while lab trials demonstrated that an infra-red (IR) oven is capable of supplying ample heating for the warm-forming process, it did not appear to be the best solution for the production application due to the need for significant IR lamp overheating to achieve production-feasible heat-up times. Over-heating was believed to present the risk of melting the blank if the conveyer system were to stop for any period of time. The team fabricated and evaluated a laboratory-level conduction heater methodology. Conduction heating is believed to be a cost-effective and robust method of heating aluminum sheet. Laboratory tests indicated that forming temperatures can be reached within cycle time requirements of 6 to 10 jobs per minute.

In general, moly-disulfide lubrication produced equal or slightly inferior cup height in comparison to BN-coated samples, with values in the range of 18-21 mm. The Fuchs Lubricants 216 wax-based varieties with BN or moly-disulfide produced the best results. 216-BN was found to be the best lubricant exhibiting a cup height of 25 mm. Because it is a wax-based lubricant, a heavy, tenacious brown stain forms on the cup surface due to curing of the polymer base and bonding to aluminum. Future work may consider development of economical cleaning solutions for this lubricant.

For the 5182-O Al sheet alloys studied in the warm forming temperature range of 200-350°C and in the strain rate range of 0.015-1.33 s^{-1}, the following conclusions can be drawn:

- Uniaxial tensile elongation increases with increasing temperature and decreases with increasing strain rate. The maximum tensile elongation observed ranged between 60-100% at 350°C.
- Strain-rate sensitivity increases with increasing temperature, and the strain-hardening rate increases with increasing strain rate in keeping with dynamic recovery effects. Strain-rate hardening is deemed to play a dominant role in enhancing the elevated temperature plasticity in tensile deformation.

Dynamic recovery effect increases with increasing stress level. And, at a specific stress level, the total amount of recovery effect increases with increasing temperature and/or decreasing strain rate.

Lubricant Studies: Fuchs lubricant 216 BN produced the best cup height of all formulations studied, exhibiting a cup height of ~25 mm, and appears to be a feasible lubricant for use in the scale-up demonstration. Cleaning options and methodologies will be defined during the demonstration trials.

Die and Blank Thermal Analyses: modeling performed by GM during 2005 completed the development of an FEA for determining optimal heater specifications for the tooling/process design. Future work on this task will verify FEA results against actual thermal data from the demonstration experiments. These data will then be incorporated into the FEA for determining optimal heater specifications for future OEM tooling/process design use.

Technical Cost Model: preliminary technical cost feasibility is positive and will be verified following the demonstration trials. Additionally, the model will be adjusted based on knowledge gained from the demonstration run. The cost model will allow warm forming of aluminum to be compared to conventional steel stamping and multi-piece assembly as a function of volume.