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Technical and Cost Study of Superplastic Forming of a Lightweight Aluminum Door Structure

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The expanded forming limits associated with superplastic forming (SPF) makes it an attractive option for the manufacture of complex parts from aluminum sheet. In this work SPF is used as an enabling technology to remove cost and mass from a multi-piece aluminum door inner structure. In the new design, panels manufactured using SPF are applied to consolidate parts and eliminate the use of expensive castings and stampings. The functional requirements of the new door system were confirmed with CAE while the ability to superplastically form the parts was confirmed with unique finite element tools specifically developed for the process. Finally, a technical cost model was applied to determine the cost of the SPF parts and to compare them with the actual part costs of the original design.

Keywords aluminum, automotive, material selection, non-ferrous metals, shaping, stamping

1. Introduction

In the continuing effort to reduce vehicle weight in order to achieve improved fuel economy, the automotive industry is constantly looking at alternative manufacturing processes to reduce the cost of applying lightweight materials in vehicle body construction. One material which is consistent with existing manufacturing processes and has attractive qualities such as low density, good mechanical properties, and high-corrosion resistance is aluminum. It has been estimated that replacing steel with aluminum in the body-in-white and closures can result in weight savings in the range of 40-60% (Ref 1). Aluminum has been successfully implemented in vehicles such as the Jaguar XJ model which resulted in a weight savings approximately of 82 kg (180 lb) while producing a vehicle that is 40% stiffer than the model from the previous generation (Ref 2). However, manufacturing with aluminum sheet is a more expensive option as compared with conventional steel. Superplastic forming (SPF) is a process that can help reduce this cost penalty.

The ability to achieve large strains to failure coupled with extremely low-flow stresses makes SPF an attractive option for the manufacture of complex parts from aluminum sheet (Ref 3). SPF is typically accomplished with a single-sided die where the sheet is heated to an elevated temperature and gas pressure is applied to one side in order to push the sheet into the tool. The single-sided tool is far less expensive than matched tooling and can make SPF an ideal process for low-volume production where investment must be minimized. Other product development and manufacturing benefits associated with SPF include elimination of springback, part consolidation, and increased design freedom (Ref 4).

While SPF has several advantages over conventional stamping, technical challenges such as slow forming rates and high-material costs have thus far limited the process to low-volume vehicles. A recently developed SPF process at Ford, named Ford Advanced Superplastic-Forming Technology (FAST) enables SPF to be cost-effective for significantly higher-volume applications, while preserving the low-investment aspects of the process. The FAST process is based on a suite of new technologies that decrease the overall cycle time and cost of SPF (Ref 4). The new technologies, thus, includes die designs that combine aspects of stamping with SPF, flexible automation for blank heating and loading, automated part extraction and cooling, as well as determination of optimal forming parameters through CAE simulation. A graphical representation of the fully integrated FAST process is shown in Fig. 1 (Ref 5).

The advantages of the FAST process are demonstrated in this paper with a redesign of a production aluminum door structure that is only possible with the expanded forming limits associated with SPF. The current door architecture is manufactured from castings, stampings and extrusions, and requires significant investment in tooling. The strategy employed in this study was to replace the relatively expensive castings and stampings with parts that are formed with the FAST system. Additionally, the use of SPF allows for part consolidation and the elimination of one part. The functional requirements of the new door system design were confirmed with CAE while the ability to manufacture the required parts from SPF was simulated and deemed feasible with the unique finite element (FE) tools utilized in the FAST process. Finally, the FAST technical cost model was applied to determine the cost of the SPF parts. This purpose-designed cost model accounts for all aspects of the cost to produce parts with the FAST system and was a critical tool in the development of the process. Cost

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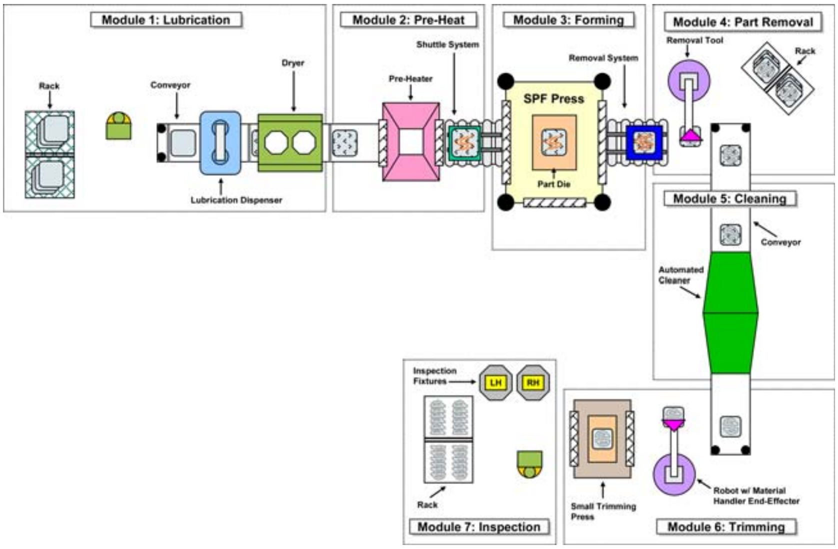


Fig. 1 Graphical representation of the fully integrated FAST process

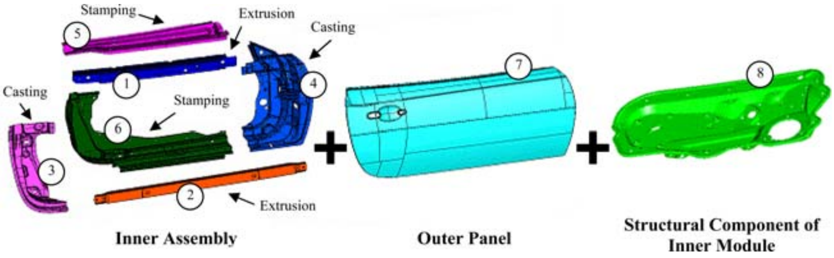


Fig. 2 Schematic of the production door architecture

estimates of the new SPF parts were compared with the actual costs of the current design. Assembly costs were not considered in this analysis.

2. Production Door Design

The architecture of the production of aluminum door investigated in this work can be segmented into three categories: the inner assembly, the outer panel and the structural panel of the inner module. The inability to fabricate a one-piece door inner stamping from aluminum forced the design team to construct an inner assembly that utilizes components made with various manufacturing techniques. A total of six parts are used including two extrusions, two castings and two stampings. The incorporation of different manufactured forms such as castings and extrusions enables design features such as beading, ribbing and local gauge increases that are not achievable in a single stamped component. Once assembled using self-piercing rivets, the inner assembly is attached to the stamped outer panel during the hemming operation to produce the door-in-white. The structural panel of the door inner module, also a stamping, is then bolted to the door-in-white later in the assembly process (trim and final). All of the components as well as a 'high-level' assembly process are shown in Fig. 2.

3. SPF-Intensive Design Proposal

3.1 Design Concept

The strategy deployed in the redesign of the door architecture focused on replacing the inner assembly and structural panel of the inner module with fewer, less-expensive parts manufactured using the FAST process. Currently, the inner assembly is composed of six parts—all fabricated using various manufacturing techniques. Adding to the structural panel of the inner module yields a part count of seven. In the new door design, the expanded forming window associated with SPF allows the formation of a single piece door inner, similar to that which is used in steel door construction. An illustration of this inner panel is shown in Fig. 3. Note the large opening in the center of the panel that allows for the installation of various hardware components such as the window regulator.

To strengthen the hinge and latch areas of the door inner, two separate reinforcements are assembled to the one-piece panel using self-piercing rivets. Both of these components, known as the latch and hinge reinforcements, are also manufactured using the SPF process—yielding a total of three SPF components used in this architecture. Combining these SPF parts with the two extrusions used in the current construction (parts (1) and (2) in Fig. 2) along with the carryover design for the outer belt-line reinforcement (part (5) in Fig. 2) produces a door inner assembly that eliminates the need for the inner module. Although the assembly implications are not discussed in this paper, it should be noted that the elimination of one part would more than likely improve the overall dimensional control as well as lower the associated joining costs. Finally, in similar fashion to the current design, the carryover outer panel is attached to the inner assembly during the hemming operation. A total of seven parts are used in this SPF-intensive door construction as compared to eight components in the current design. A schematic of this new door architecture is shown in Fig. 4.

3.2 Design Verification Process

To verify the functionality of the SPF-intensive door architecture, four system design specifications (SDS) were identified as critical. These SDS requirements include belt squeeze, door drop-off (self-weight), door sag, and static torsion. All these specifications were all evaluated using CAE simulation techniques which were in accordance with the standards outlined in the Ford Motor Company corporate engineering test procedures (CETP).

The FE models used in the CAE simulation of the production door structure and the SPF-intensive door architecture were generated and solved utilizing the IDEAS software tool. The technique used to create the FE meshes involved the utilization of linear triangular and quadrilateral shell elements. The production door mesh consists of 40,334 elements with an average element size of approximately 15 mm whereas the SPF-intensive model incorporates 36,206 elements with a slightly larger average element size than the mesh for the production door. A comparison of these FE meshes illustrating the level of detail used in the models is shown in Fig. 5.

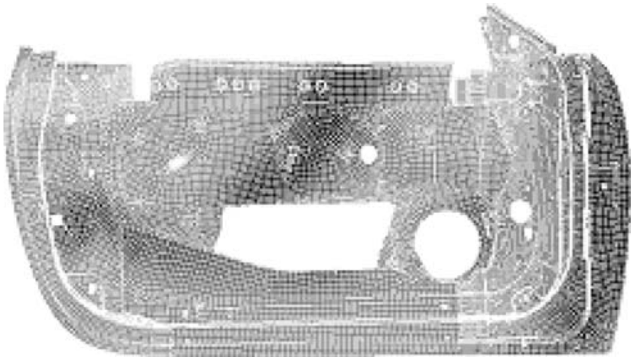


Fig. 3 Door inner panel manufactured using the FAST process

All the joints or connecting points between the components for each assembly were assumed to be rigid and modeled with the ‘1D rigid-element’. The ‘spider-web rigid-element’ was used in critical joints to spread the load over large areas. In the case of the SPF-intensive FE mesh, the shell element thickness of the door inner panel was locally increased in the hinge and latch areas (shown in blue in Fig. 5(b)) to simulate the addition of reinforcements—thus eliminating the need to create FE meshes for these parts. Therefore, the shell elements of the door inner panel in the SPF model have a local thickness of 3.7 mm in the hinge and latch areas and a thickness of 1.2 mm everywhere else. A brief summary of the model inputs for each design proposal is shown in Table 1 and 2.

A summary of the analytical results for both the production of door structure and the SPF-intensive door proposal is shown in Table 3. The estimated weight savings of the SPF-intensive proposal as compared to the current design is shown in Table 4. As shown in Table 3, neither the production nor the proposed SPF-intensive CAE version achieves the acceptability level of the *belt squeeze* SDS requirement. However, the proposed design is found to be similar in performance with the production door structure. This non-conformance of either architecture is deemed acceptable since the door system utilizes dual regulator channels—the current CETP does not account for this type of design structure. In comparing the remaining specifications, both door systems achieve the acceptability levels of the *door drop-off* and *door sag* requirements, although the door sag test of the SPF-intensive proposal lags the production design by approximately 16%. However, the proposed design does exceed the performance of the current structure in the *torsional rigidity* test. An improvement in the deflection of roughly 12% may be attributable to the ‘inverted U-shape’ bridge that is formed by the connection of the latch reinforcement, belt inner reinforcement and hinge reinforcement (parts (3), (1) and (4) in Fig. 4). It should be noted, though, that neither door system meets the SDS requirement for the torsion test. However, the SPF-intensive door displays superior torsional rigidity than that of the production door. An illustration of the door deflection under torsional load is shown in Fig. 6 for both architectures.

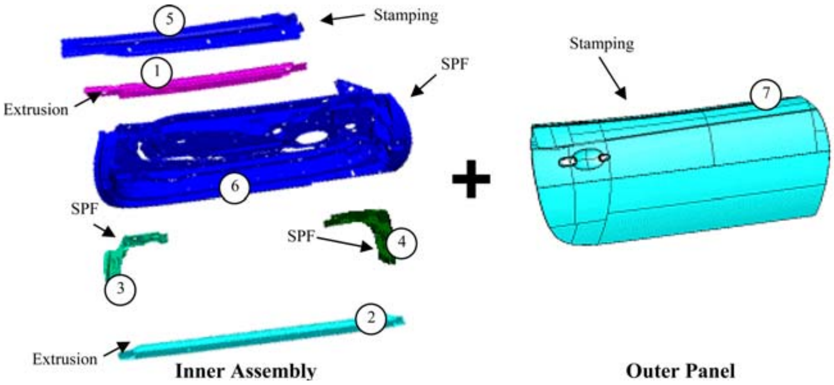
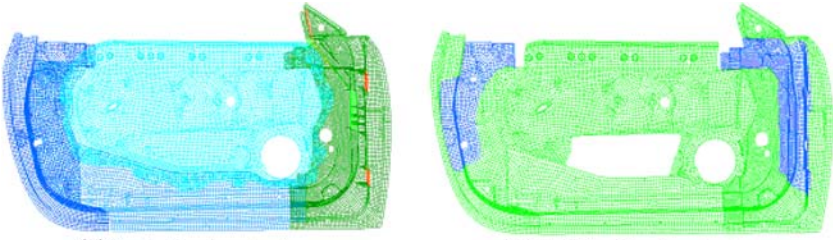


Fig. 4 Schematic of the SPF-intensive door architecture



(a) Production door structure

(b) SPF-intensive door structure

Fig. 5 FE meshes of the production door inner assembly and the SPF-intensive proposal. (a) Production door structure (FE mesh); (b) SPF-intensive door structure (FE mesh)

Table 1 Material and thickness assumptions used in the production door structure FE analysis

No	Part name	Description	Part thickness, mm	Part material	Modulus of elasticity, GPA
1	Reinf Frt Door Inr @ Belt	Extrusion	2.0	6082-T6	72
2	Intrusion Beam Front Door	Extrusion	2.0,4.5	6082-T6	72
3	Reinf Frt Door Inr @ Latch	Casting	2.0	AlSi10MgMnFe	72
4	Panel Frt Door Inr @ Hinge	Casting	2.2	AlSi10MgMnFe	72
5	Reinf Frt Door Otr @ Belt	Stamping	1.8	5754	72
6	Panel Frt Door Inr @ Latch	Stamping	1.8	5754	72
7	Panel Frt Door Otr	Stamping	0.8	6111-T4	72
8	Structural Comp of Inr Module	Stamping	1.2	5000 Series	72

Table 2 Material and thickness assumptions used in the SPF-intensive door structure FE analysis

No	Part name	Description	Part thickness, mm	Part material	Modulus of elasticity, GPa
1	Reinf Frt Door Inr @ Belt	Extrusion	2.0	6082-T6	72
2	Intrusion Beam Front Door	Extrusion	2.0,4.5	6082-T6	72
3	Reinf Frt Door Inr @ Latch	SPF	2.5	5083	72
4	Panel Frt Door Inr @ Hinge	SPF	2.5	5083	72
5	Reinf Frt Door Otr @ Belt	Stamping	1.8	5754	72
6	Panel Frt Door Inr	SPF	1.2	5083	72
7	Panel Frt Door Otr	Stamping	0.8	6111-T4	72

Table 3 CAE and test results of critical SDS requirements for the current and SPF-intensive door

No	SDS description	Load req.	Acceptability level, mm	Production test data, mm	Production CAE results, mm	SPF design[a] CAE results, mm
1	Door belt static strength (belt squeeze)	180 N each side	<3	3.95	4.72	4.9
2	Door drop-off (self-weight)	W + 177.5N	<1	na	0.31	0.34
3	Door sag	g + 1000N @ latch	<20	6.96	5.51	6.41
4	Door torsional rigidity	180 Nm	<4	na	5.24	4.6

(a) The thickness of the SPF door inner panel is 1.2 mm and the gauges of both the SPF hinge and latch reinforcements are 2.5 mm

4. Manufacturing Feasibility

4.1 Forming Strategy

The three superplastically formed panels of the proposed door inner design are formed using two non-planar dies. The inner tub is made with one die and the two reinforcements are made together in a second die. A non-planar SPF die is utilized that incorporates a contoured seal surface that matches the general shape of the panel being formed. Unlike matched stamping tools, only the outer seal surface (or binder area) acts to mechanically shape the perimeter of the blank. The advantage of this approach is that the general shape of the panel can be formed mechanically when the die halves close together. While the fine details of the panel are formed with gas pressure, the use of pre-forming reduces the level of overall deformation needed during gas forming and minimizes the amount of thinning. However, the level of mechanical pre-forming is limited by the propensity of the panel to wrinkle since there is no blank-holder to restrain the perimeter of the sheet. Three-dimensional FE simulation is used to establish if wrinkling will occur when the die is closed.

Since all three of the superplastically formed panels have similar radii and contours, only one component, the door inner panel, was selected for SPF manufacturing feasibility analysis. The forming strategy identified for this panel was to mechanically

Table 4 Estimated mass of the current and SPF-intensive door designs

Description	Production CAE results	SPF-intensive CAE results^a	Weight savings %^{b}
Mass (kg) of door structure	13.1	11.6	11.4%
Mass (kg) of door inner assembly less common parts	5.8	4.3	26.0%

(a) The thickness of the SPF door inner panel is 1.2 mm and the gauges of both the SPF hinge and latch reinforcements are 2.5 mm, (b) Based on CAE

pre-form the part following the contour of the outer trim surface and then use gas pressure to finish the final shape. The potential of wrinkling in the panel as a result of the pre-forming was deemed inconsequential due to the 'sweeping-contour' shape of the part design (resulting in single-curve bending of the sheet during the forming process). Due to the relatively shallow depth of the panel with a low-aspect ratio (ratio of part depth to width), full three-dimensional analysis was deemed unnecessary. However, this approach would be required in a 'clean-sheet' design of any new SPF component. It is important to note that draw depth and aspect ratio are critical parameters in the SPF process and, in general, the difficulty in forming increases with both cavity depth and aspect ratio.

Other design features of the door inner panel that are important to the SPF process are the small radii located throughout its geometry. The smallest radii are approximately 4 mm and based on a initial sheet thickness of 2 mm yield a ratio of die radius to sheet thickness (r/t) of two. This low r/t ratio suggests that a risk of localized necking may occur when forming over these small radii. (Ref 6, 7) Therefore, a two-dimensional (2-D) analysis using the implicit FEA code ABAQUS was conducted to predict any occurrence of localized necking. This type of 2-D analysis is referred to as sectional analysis and has been shown to be an effective method for evaluating the risk of localized necking (Ref 6, 7). To begin this analysis, critical sections of the panel were cut in CAD and modeled with FEA. These sections are shown in Fig. 7. Section 1 and 3 were assumed to be in a state of plane strain and Section 2 was assumed to be analogous to a 2-D axisymmetric state. The sheet blank was modeled using six layers of 2-D continuum elements. The material model was constructed using high-temperature tensile test data measured from the superplastic AA5083 alloy (Ref 8). In general, the strain rate sensitivity of a material is a useful metric for evaluating its ability to resist necking. As part of this analysis, the rate sensitivity of the SPF AA5083 alloy was determined experimentally (Ref 8) to be approximately 0.39 for gas forming operations with strain rates between 10^{-3} s^{-1} and 3×10^{-3} s^{-1}. The higher the strain rate sensitivity the more uniform the final thickness and the less risk of localized necking. Instead of using the rate sensitivity of 0.39 in the simulation, a conservative approach was taken and the rate sensitivity was artificially reduced to 0.25. The reason for lowering this value was that if severe necking did not occur at this low rate then the risk of necking would be essentially zero during the experimental forming trials using this alloy. Although SPF-grade 5083 can tolerate thinning in excess of 60%, a criterion was established to limit thinning to 50% in order for the door inner panel to be considered feasible.

A standard pressure-time curve was applied to completely form the part. Based on the simulation of each section, the thickness profile was plotted with respect to the node number (labeled in consecutive order across each section). The maximum thinning of 45% was observed in Section 1 and 3. In Section 1, the maximum thinning occurred in the hinge area of the panel on the radius that transitions from the flange into the door cavity. In Section 3, the maximum thinning was near the bottom of the door inner panel on the radius that transitions from the flange into the cavity. Section 2 did not experience thinning above 40%. The thickness profile for Section 1 is shown in Fig. 8. Note the spikes in thinning profile correspond to the radii at the front and back walls of the part. Although thinning was predicted to be as much as 45%, a localized neck did not develop in the simulation at these locations. All of the observed spikes remained on each radius and did not slide around the radius onto the flat wall surface. Such a condition can lead to part splitting and was not observed in any of the sectional results (Ref 7).

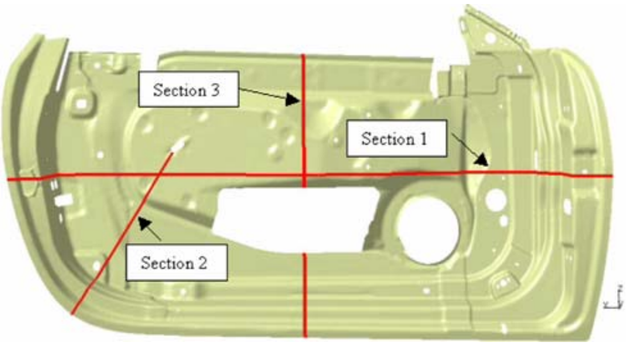
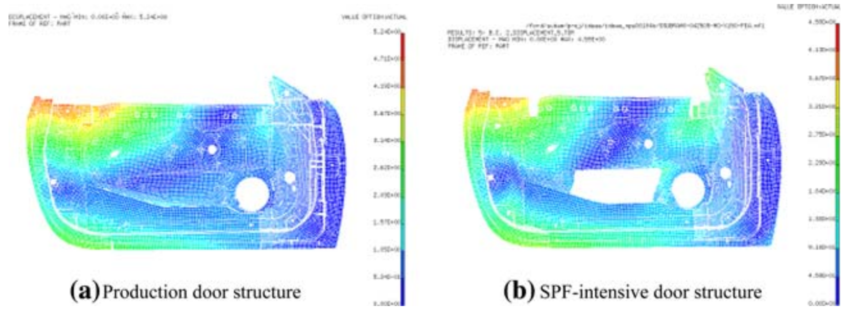


Fig. 7 CAD of the proposed inner panel showing the three sections evaluated with 2-D FEA


(a) Production door structure

(b) SPF-intensive door structure

Fig. 6 Stress plots of the door deflection under torsional load for the current and proposed designs. (a) Production door structure (FE mesh); (b) SPF-intensive door structure (FE mesh)

To improve the thickness profile there is a potential opportunity to employ a gas pre-forming step into the process. A pre-form creates length of line and preserves metal thickness in critical regions of the die. The pre-form geometry is made during the first of two stages of gas forming. It is important to note that both stages of the forming cycle would be performed in the same tool as detailed in Fig. 9. The thickness profile resulting from applying this pre-form technique (Fig. 10) resulted in a reduction in the maximum thinning to less than 40%.

The feasibility of manufacturing this panel is independent of the decision to use gas pre-forming. Based on the sectional analysis results in which a conservative value for the strain rate sensitivity was used to predict a maximum thinning of approximately 45%, the door inner panel is deemed feasible for manufacture using the FAST process.

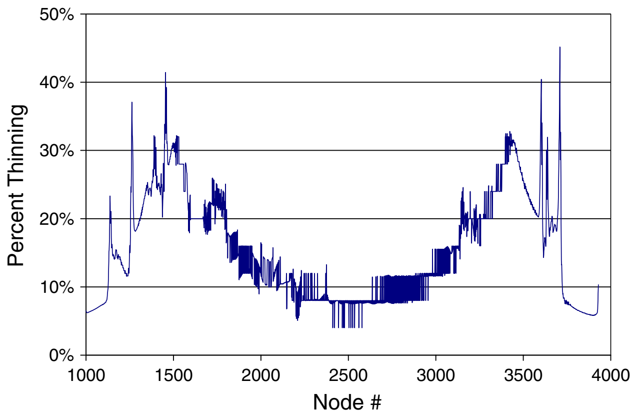


Fig. 8 Thickness profile of Section 1 predicted with sectional analysis

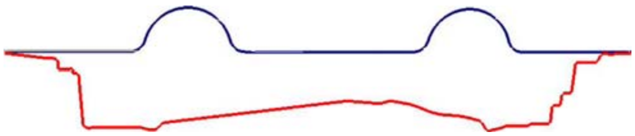


Fig. 9 A gas pre-forming concept for Section 1 of the door inner panel

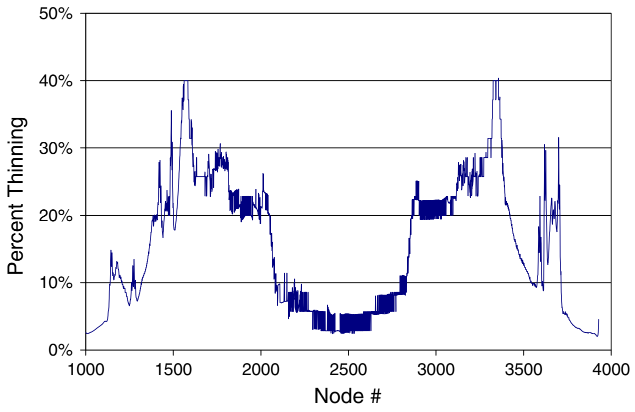


Fig. 10 Thickness profile of Section 1 predicted with FEA sectional analysis and including a gas pre-forming step in the forming cycle

4.2 Die Design, Tooling Investment and Forming Parameters

The development of the SPF tool for the door inner panel was based on the FAST die design guidelines. Figure 11 illustrates a schematic of a two-stage SPF die that incorporates gas pressure pre-forming into the process (Ref 9). To control the gas pressure on both sides of the sheet during a two-stage SPF cycle, this proprietary design was specifically developed for the FAST process. Unlike the schematic of Fig. 11, the die for the door inner would also have a non-planar binder as discussed above in Section 4.1.

An important advantage of the FAST die technology is that it does not require the investment costs associated with conventional stamping tools. Unlike traditional dies, SPF tools are not matched, they are not hardened, nor do they experience the severe impact loading that is required in conventional stamping tools. For these reasons as well as others not mentioned, FAST tooling costs can be as little as 10% of the cost of conventional stamping dies. The tooling cost for the door inner panel was estimated to be \$45,000 and the die that is used to manufacture both reinforcements was estimated to be \$39,000 (\$168,000 for all three parts for both LH and RH doors).

Forming times were estimated using a standard calculation based on maximum thinning and forming strain rate targets. Using a maximum thinning percentage of 45% in biaxial stretching (which yields an effective true strain of 0.597) and factoring in a target strain rate of 0.002 s^{-1}, the forming time of the inner tub was estimated at 0.597/0.002 s^{-1} = 298.5 s (~5 min). It was also determined that the forming time for the latch and hinge reinforcements would also be approximately 5 min.

In order to achieve an acceptable final part thickness for the door inner panel, the blank was assumed to have a starting thickness of 1.5 mm. This is a conservative estimate and more than accounts for the additional thinning that is typical in SPF. The estimated blank size for this panel was 1575 mm × 915 mm (62″ ×36″) and the material utilization was estimated to be 58%. The die to produce both reinforcements would require a blank approximately 1015 mm × 915 mm (40″ × 36″) with a material utilization of approximately 50%.

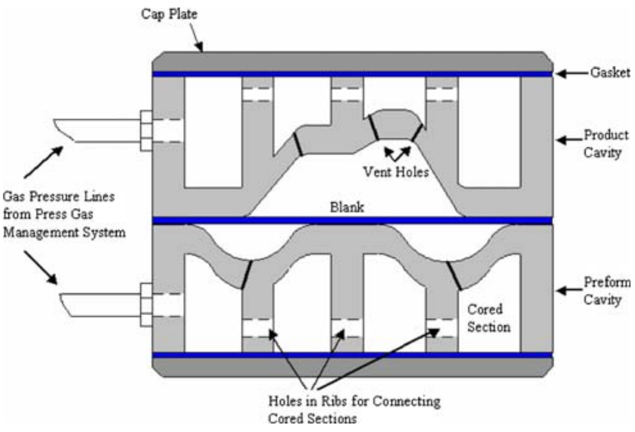


Fig. 11 Schematic of a two-stage SPF die

5. Cost Comparison

5.1 Introduction to FAST Technical Cost Model

The FAST financial model is a parametric, interactive computer tool that estimates the fully accounted cost (FAC) associated with producing a part using the FAST process. The model can account for both the blanking and forming stages of the entire part-making process. The SPF segment of the model partitions the process into six (6) stations or modules: lubrication, pre-heat and shuttle, formation, removal, cleaning and trimming. The data inputs requested by these modules are structured in such a way as to identify the quantities of tooling and equipment, current values and cycle times required for each operation/task, a common method used in Activity Based Costing. Upon completion of the input sheets, a summation of the entered investment costs can be observed in the Total Process Summary worksheet. This information is then used in the Depreciation Charts spreadsheet to determine the resulting value of all the equipment (based on the useful life projections) at the end of the product life cycle. These depreciated values are then used in the Initial Computations worksheet where the user can view the majority of the cost calculations. It is in this worksheet that the foundation of the model, the line utilization rates (based on the operating patterns entered on the input sheets), and all of the subsequent calculations take place. Once the line availability and required production times have been computed, the model can then proceed to estimate all of the costs that make up the variable and investment items. The variable item is composed of seven (7) categories that include material, direct labor, indirect labor, MRO (maintenance, repair and other) labor, consumables (electricity, lubrication and cleaning agent), maintenance (parts and supplies) and insurance. The investment cost is categorized into four (4) items that include tooling, equipment depreciation, facilities (depreciation and tax) and cost of capital (applied to equipment and facility items only). It should be noted that the tooling cost is not incorporated into the FAC. This cost is shown as a lump sum. After all of the initial computations are performed, the data is then displayed in an accounting format that depicts the year-over-year costs associated with each category.

5.2 Assumptions used in the FAST Cost Analysis

In calculating the costs incurred to produce the door inner panel, latch reinforcement, and hinge reinforcement for the door structure, the following facility assumptions were used in the model.

- Facility assumptions

1. New FAST facility
2. Press: 1.4 m×2.4 m heated platen, 800-ton, single-action, 2-sided access
3. Warm die change performed with die cart and extraction device (6 h)
4. Tool maintenance per year = % of original tooling cost
5. Cost of debt rate = 8.0% (before taxes), 5.2% (after taxes)
6. Lot size for each run = 300

Table 5 Cost comparison between the production door and the SPF-intensive door for both LH and RH sides

	Piece cost/door set	Tooling cost/door set
Production door structure	~$315	~$4,449,000
SPF-intensive door architecture	$297	$858,171

5.3 Cost Model Results

The FAST cost model was used to estimate the FAC of the door inner panel, latch reinforcement and hinge reinforcement in the SPF-intensive door design (parts 3, 4 and 6 in Fig. 4). The estimated FAC included all of the costs associated with producing each part except the tooling costs. This dedicated cost is shown separately and is assumed to be paid in full prior to production for each component.

The comparison of the production door structure cost to the proposed SPF-intensive door architecture cost is shown in Table 5. This comparison highlights the piece cost and tooling cost per door set for each structure. These costs do not include the piece price or the tooling cost for the door outer panel, which is assumed common between the two designs. The SPF-intensive proposal exhibits a tooling cost savings of approximately $3.6 M and a piece price savings of roughly $18 per vehicle. This analysis is for just the parts of the door and does not include joining. However, it is assumed since one part has been eliminated that joining costs will be somewhat lower for the SPF-intensive design.

6. Summary and Conclusions

In this work the FAST process was used as an enabler to develop a lower cost design for a production door inner structure. The FAST CAE tools were used to ensure manufacturing feasibility while standard FE analysis was applied to validate the functionality of the new door structure. The costs of the SPF-intensive design were estimated using the FAST technical cost model and compared with the actual costs for the production door. The model showed the new design to be approximately $18 less expensive per vehicle with a savings of over $3.6 million in tooling costs. The approximate 80% reduction in tooling costs (excluding the door outer) is a direct result of replacing the relatively expensive tools for castings and stampings with low-cost SPF tools.

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