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Overview of Superplastic Forming Research at Ford Motor Company

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In an effort to reduce vehicle weight, the automotive industry has switched to aluminum sheet for many closure panels. Although the application of aluminum is compatible with existing manufacturing processes and has attractive qualities such as low density, good mechanical properties, and high corrosion resistance, it has less room-temperature formability than steel. The expanded forming limits that are possible with superplastic forming can significantly improve the ability to manufacture complex shapes from materials with limited formability. Aluminum closure panels produced by superplastic forming have been used by Ford Motor Company for over a decade. However, applications have been limited to low-volume, specialty vehicles due to the relatively slow cycle time and the cost penalty associated with the specially processed sheet alloys. While there has been substantial research on the superplastic characteristics of aluminum alloys, the bulk of this work has focused on the development of aerospace alloys, which are often too costly and perhaps inappropriate for automotive applications. Additionally, there has been a limited amount of work done to develop the technologies required to support the higher production volumes of the automotive industry. This work presents an automotive perspective on superplastic forming and an overview of the research being performed at Ford Motor Company to increase the production volume so superplastic forming can be cost competitive with more traditional forming technologies.

Keywords aluminum, automotive, superplastic forming

1. Introduction

Pressure to reduce vehicle weight has forced automotive manufacturers to look to alternatives to steel for vehicle body construction. One material compatible with existing manufacturing processes and attractive qualities, such as low density, good mechanical properties, and high corrosion resistance, is aluminum. Although it has been estimated that replacing steel with aluminum in body-in-white (structural skeleton of the vehicle) and closures can result in weight savings as high as 55% (Ref 1), aluminum has lower room-temperature formability than steel. This can result in restrictions in outer body panel geometry, which can significantly limit automotive design. Additionally, the limited formability can require that parts be split into two or more separate, easier to form panels, which increases both cost and complexity. The inner panel of a door is an example of a part that can be stamped in one piece from steel, but may take up to four separate parts with aluminum. This adds cost in both the additional dies to form the separate parts and the fixtures and assembly costs to join them. The assembly process may also introduce additional dimensional variability as compared with one-piece construction. Superplastic forming (SPF) is a process that has the potential to remove these design restrictions.

Superplastic forming is typically accomplished by blow forming where a sheet blank is clamped in a die and gas pressure is applied to one side. As shown in Fig. 1, this simple forming technique encompasses a single one-sided die rather than a matched pair, and, therefore, tooling is significantly less expensive than that for a conventional stamping. Furthermore, the very low forces needed to form the material at elevated temperatures allows for the use of cast iron dies instead of the harder-to-work tool steels. Other product development and manufacturing benefits associated with superplastic forming include elimination of springback, part consolidation, and increased design freedom.

Superplastic forming is now considered a standard process in several industries including aerospace, rail, and architecture. The relatively inexpensive tooling required for SPF is a perfect fit for the lower production volumes of these industries, as compared with automotive. The low-investment attributes of superplastic forming also make it an attractive option for lower-volume niche products in the automotive industry. In fact, superplastic forming has been used at Ford Motor Company for more than ten years and is currently used to manufacture the closure panels on such vehicles as the Ford GT and the Aston Martin Vanquish.

Significant advances have been made in superplastic forming over the past 30 years. New alloys that combine good superplastic flow with excellent postformed properties have allowed the aerospace industry to replace complex, multipiece components with single, superplastically formed panels (Ref 2). Developments in low-cost ceramic tooling have further helped develop SPF as a low-investment choice for forming

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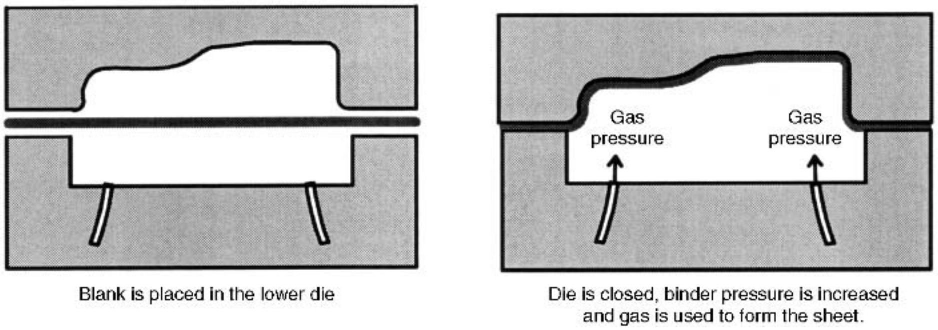

Fig. 1 Schematic of a single-sided SPF tool shown before and after gas pressure forming

complex three-dimensional components (Ref 3). While these advances have been critical to the continued application of SPF, development has mostly focused on applications that have relatively low production volumes as compared with automotive. The majority of the work on materials has been on alloys that are typically cost prohibitive and perhaps not appropriate for automotive applications. Additionally, there has been a limited amount of published work on developing superplastic forming as a manufacturing process addressing topics such as automation, lubrication, and pre- and postforming technologies that serve to decrease overall component cycle time.

To expand the use of SPF in the automotive industry, new technologies are needed that will both decrease the total cost of the process while also increasing the production volume in which the process is cost effective. This will require novel innovations to reduce the material cost penalty as well as a variety of modifications to the manufacturing process that can decrease both the forming time as well as the overall process cycle time. Research and development efforts at Ford Motor Company are concentrated on topics such as materials, die technology, press design, lubrication, automation, and pre- and post-forming technologies that serve to decrease overall component cycle time. One key to developing a cost-effective superplastic forming process for automotive applications is to adopt a systems approach where the integration of SPF into up- and downstream operations is considered. This work presents an overview of the development strategy and research efforts at Ford Motor Company to develop SPF for automotive applications.

2. Strategic Direction for SPF

2.1 SPF Cost Structure

The automotive industry utilizes a wide spectrum of manufacturing processes to accommodate different vehicle production volumes. To develop the most cost-efficient production strategy, investment in tooling must be balanced with variable cost for a given volume. For very low volume production, such as the case for the specialty car manufacturers, minimization of investment is paramount. This is similar to the aerospace or rail industries in which annual production volumes may be less than 1000. In these cases, higher material costs and somewhat longer cycle times can be tolerated in lieu of lower investment in tooling and equipment (Ref 4). For higher-volume vehicles, the total volume over a six-year cycle can be several million vehicles. In this case, the fixed cost is spread over the millions of vehicles produced, and, therefore, minimizing variable cost through lower-cost materials and faster cycle times is critical.

Technical cost modeling is a key tool in the selection of production forming processes as well as the development of new processes. These models break down the production process to key steps for which all of the costs (fixed and variable) can be analyzed. Models are typically part specific and can be used to understand the volume sensitivity of a specific manufacturing process. In Fig. 2, the fully accounted cost of an aluminum hood as a function of yearly production volume is shown for SPF and conventional stamping (Ref 5). The analysis indicates that the SPF process is a cost-effective option, as compared with stamping, for production of an aluminum hood up to a yearly volume of approximately 5000 vehicles. This is a direct result of the lower tooling costs (investment) required in this process as compared with that of conventional stamping. For quantities greater than 1000 vehicles, the increased cost of material and the longer cycle times associated with SPF cause the incremental price of the aluminum hood to level off with increases in volumes. At higher volumes, the incremental cost for the stamping process continues to decrease because the higher investment is spread over a larger number of vehicles. Hence, for larger production volumes, the conventional stamping process becomes a better solution with respect to overall cost.

To further understand the cost structure of the SPF process, the major cost drivers were extracted from the model. Figure 3 (Ref 5) shows the effect of different variables on the production cost of an aluminum hood manufactured via SPF. Along the centerline of the graph the assumptions for a conventional SPF process are shown. The effects of decreasing or increasing these values on the cost of the hood are then shown to the left and right, respectively, of the centerline. The largest cost factor in SPF manufacturing is the price of the specially processed aluminum sheet. A decrease of material price from $3.50 to $1 per pound reduces the unit cost of the hood by approximately $75. Reducing the cycle time is the second largest factor with a reduction of one-third (6-2 min) resulting in a cost reduction per hood of $35. These results indicate that development work should focus on decreasing, or possibly eliminating, the cost penalty of the aluminum sheet as well as modifications to the manufacturing process that can help to decrease part-to-part cycle time.

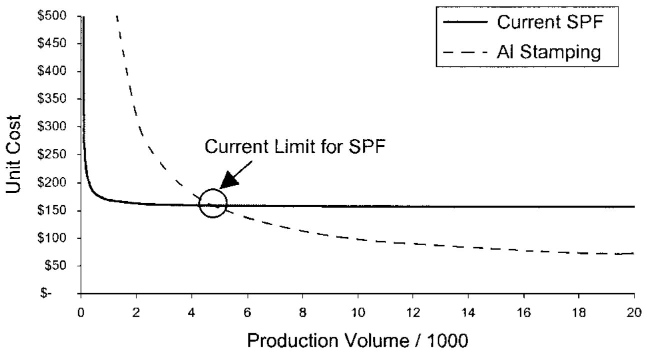

Fig. 2 Results of a technical cost model showing the cost of an aluminum hood as a function of production volume (per year) for SPF and conventional stamping. Source: Ref 5

2.2 Development Strategy

To expand the production volume in which SPF is cost effective, a systems approach needs to be taken where the up- and downstream processes are considered. Processes such as blanking, lubrication, preheating, part loading/unloading, cleaning, trimming, and assembly are critical with respect to developing a cost-effective solution. Additionally, selection of these various processes must be done to match production volume to optimize cost effectiveness. That is, the processes selected prior to and after SPF require a systems-based solution, which is a function of production volume. The technical cost model is a key tool in determining which technologies are best suited for specific applications.

2.2.1 Low-Volume Applications. Production of very low volume, niche automobiles requires careful control over investment. Superplastic forming processes for these applications are centered around low-cost tooling and manual operations. Blanking, lubrication application and cleaning, and part loading/unloading are performed with minimal investment and without automation. Computer numerical control (CNC) machining offers a highly flexible, low-investment process for postform trimming. Joining of the outer closure panel to the inner reinforcement can be accomplished with a flexible system such as a robotic-roll hemmer. While this type of joining is considerably slower than other alternative processes, one flexible unit can be used on various types of panels. Hence, the investment cost is shared over several different parts.

2.2.2 Medium-Volume Applications. The decision to use SPF on vehicle programs with medium production volumes (2500 to 25,000 vehicles per year) is based on either cost savings associated with part consolidation or the desire to make complex exterior closure panels that are not possible by conventional methods. While SPF can have a forming cycle time disadvantage when compared directly to other fabrication technologies, as a result of part consolidation the overall cost and fabrication time to produce an SPF closure assembly can be cost competitive. For example, aluminum door inners are usually assembled from several stamped, extruded and/or cast parts. With SPF, a one-piece inner can be formed from a single aluminum blank, similar to what is possible with steel.

The lower formability of aluminum compared with steel can limit design freedom in exterior body panels and may require concessions in panel geometry. Superplastic forming can be used in these cases to eliminate the design constraints and allow for the manufacture of very complex shapes from aluminum sheet. For some panels, the only option other than superplastic forming of aluminum to achieve a given shape is a composite plastic panel.

The use of automation in up- and downstream operations is the envisioned key enabler to supporting SPF at medium levels of production volume. Upstream operations such as laser blanking, lubrication, preheating, and part loading will drive efficiency of blank processing prior to forming, while downstream processes of robotic part removal, automated cleaning, and laser trimming will be used for postforming operations. Again, a flexible system such as a robotic roll hemmer may be used to complete the assembly. As volume increases, the cost of material must be addressed, and the previously mentioned development of lower cost aluminum sheet will play a critical role in the cost justification to use SPF.

2.2.3 High-Volume Applications. For higher production volumes the main driver for SPF is to overcome the limitation of the room-temperature formability of aluminum. In these cases, SPF needs to be used with more traditional high-volume manufacturing processes common to the automotive industry. Laser blanking and trimming operations are replaced by press trimming and blanking. Additionally, press-action flanging and hemming become necessary as roll hemming and flanging do not offer the short cycle times required to support higher production volumes. Hybrid forming processes would also need to be used to significantly decrease the forming time required to manufacture the part. A hybrid process may be either a preforming method in the die or possibly a secondary operation such as a restrike operation to fully form the part.

As noted for medium volumes, the cost of material becomes more important as the production volume increases. For high-production volumes, an increase in investment may be justified if it allows for the use of lower-cost, conventionally processed materials.

3. SPF Research and Development

3.1 Material Development

The primary alloys of interest for automotive body construction are the aluminum-magnesium alloys (AA5xxx). These materials are already used extensively in vehicle structures and closures and can be processed to have a relatively small grain size and good superplastic properties (Ref 6-9). However, Al-Mg alloys have a distinct disadvantage over the heat treatable AA6xxx alloys for class A closure panels. Closure panels are strength-driven and therefore benefit from the artificial aging that occurs during the elevated-temperature paint bake cycle. As an example, an aluminum hood manufactured from a typical AA5xxx alloy would need to be approximately 20% thicker than an AA6xxx alloy to achieve the same functionality. While research and development activities are ongoing to produce an AA6xxx alloy suitable for SPF, these materials are not yet commercially available (Ref 10).

One key aspect of minimizing material cost is to ensure that the right material is selected for the optimal process to make a specific part. While difficult-to-form parts may require premium materials that can achieve very high strains to failure, many other parts are relatively simple to form and do not

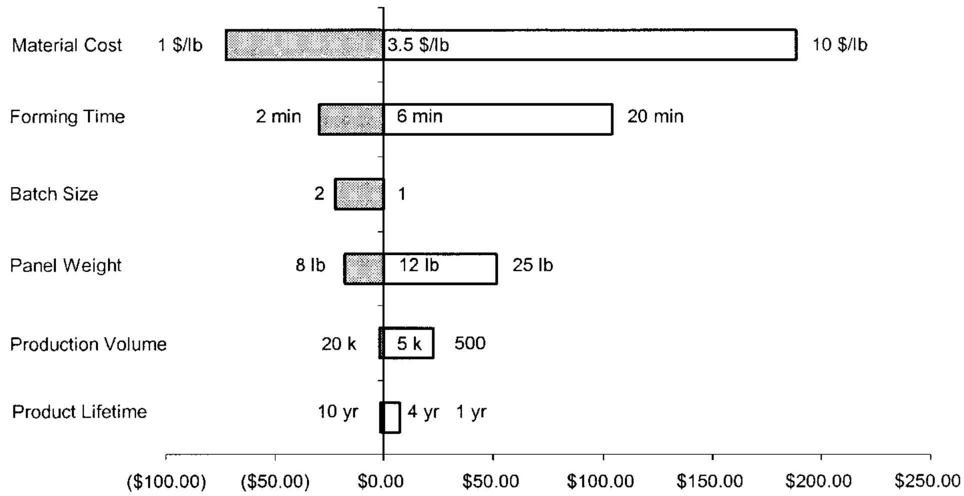

Fig. 3 Results of a technical cost model showing the effect of different variables on the production cost of an aluminum hood with superplastic forming. Source: Ref 5

require such high strains. The decision to use SPF on these types of parts may be simply to reduce investment cost. It is critical that the material selected meets the requirements to form the part. However, it is also critical for the economics of SPF that a material with substantially more SPF capability than is needed not be selected. That is, for a relatively simple part such as a hood, significant variable cost can be saved by switching to a lower-cost alloy. Since the decision to use SPF is often a function of material price, it is critical to have a method of determining material needs prior to making this decision. A process at Ford Motor Company is under development that will enable upfront prediction of the material requirements for a specific part, based on examining the part design, the target forming properties, and the initial material selection. These three items, shown at the top of Fig. 4, are interrelated as the forming targets are very much a function of the part design and the type of sheet selected. From this point, initial simulation of the forming process is performed to fully develop the forming cycle, estimate material thinning, and record the strain and strain rate histories throughout the part. This information is then compared with data gathered in the original characterization of the material to determine if it can achieve this level of performance. Additionally, a database of experiments on postformed panels is used to estimate the final in-service mechanical properties of the part. Based on these estimates, a decision can be made to either move forward with the process development, or, if the requirements of the part are not met, to redesign the part if possible, select a more formable material, or adjust the forming targets.

Further development of lower-cost alloys that possess adequate superplastic characteristics is the key to the widespread use of this technology. Recent results indicate it may be possible to use a SPF process using conventionally processed alloys to form relatively simple parts. While the grain size in these alloys may be too coarse for efficient grain boundary sliding, results indicate that good levels of formability can be achieved in deformation regimes controlled by solute drag (Ref 11). In fact, it appears that optimal forming parameters for these materials involve faster strain rates and lower temperatures than those typically associated with SPF processes (Ref 12).

3.2 Die Design and Technology

Superplastic forming in its simplest embodiment (Fig. 1) consists of blowing a sheet of aluminum into a hot, single-surface die. As noted previously, superplastic forming is a rate-sensitive process typically carried out at low strain rates. The pressure applied to the panel to force the metal into the die therefore needs to be carefully controlled so as to not exceed a maximum forming rate. This typically results in a slow forming process, which is ill suited for high-volume automobile production. Additionally, the process is a net-thinning process in which no additional material is drawn into the die cavity during forming. This can lead to excessive thinning of the panel, which may leave the part with unacceptable postformed properties. Research at Ford Motor Company on SPF die technology is focused on decreasing cycle time and improving final part thickness distribution while retaining the low-investment aspects of the process.

One method for increasing production rate is to increase the yield per cycle by forming multiple parts in one forming cycle. Nesting of parts on one large die with multiple cavities to simultaneously form several parts is a common practice to improve production capacity. Additionally, dual forming where parts are formed both up and down in the die can be used to double production volume (Ref 13). Gas pressure is introduced between the two blanks, and the pressure pushes the blanks in opposite directions toward the die surfaces.

Another method of increasing production volume is to combine elements of stamping (or mechanical forming) with SPF. This hybrid approach can reduce cycle time, thus increasing possible production volumes. The simplest embodiment of this approach is either a plug-assist die or simply a die with a nonplanar binder. In either case, some degree of mechanical forming takes place by simply closing the die. The degree of mechanical preforming possible with this approach is limited by the panel shape and its proclivity to wrinkle as the material is drawn into the die. While this process is limited in how much the blank can be shaped prior to SPF, research has shown that the drawing in of only a small amount of material before the die is sealed can significantly improve SPF performance, decrease

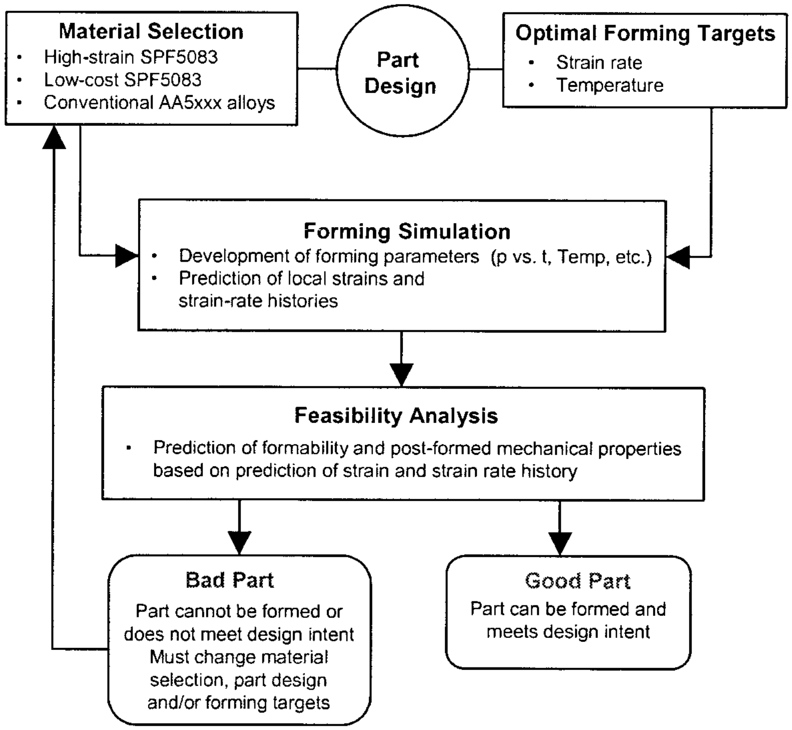

Fig. 4 Flow chart depicting the early decision-making process in alloy selection

cycle time, and provide more uniform final thickness distribution (Ref 14).

To further reduce cycle time, the degree of preforming needs to be increased so that the panel has considerable shape prior to the gas pressure forming stage. To control the wrinkling problem, a blank holder similar to that used in traditional stamping can be applied. Several processes have been used to produce a preform with a blank holder and then reverse the preform with gas pressure onto the punch (Ref 15). In some cases, the majority of the panel can be shaped in a preforming step while using the SPF process only to complete the finer details of the part. Additionally, preshaping of blanks has been applied where a significant amount of the forming is performed in a separate tool prior to SPF (Ref 16, 17). The panel is first shaped within a nonplanar die by mechanical preforming, thus leaving the finer details requiring higher strains to failure to be gas pressure formed. A preforming process similar to this has been applied by Honda Motor Company (Ref 18, 19).

A new process at Ford Motor Company has been introduced that allows both mechanical preforming and gas pressure forming into the same female cavity (Ref 20). The new process is based on lower-cost, flexible tooling and preserves the low-investment aspects of SPF. The blank-holder effect is accomplished by a cushion system built into the press and not the die. The top die is lowered until it makes contact with the SPF die surface that seals the SPF chamber. SPF gas pressure is then used to complete the part. The key concept is that the cushion system is located in the press under the cooling platen and away from the elevated temperature. This allows for the use of gas pressure cushion cylinders that are not suitable for high-temperature environments. The load from the cushion system is transferred through the heated platen with the use of pins. This design relies on the press for the second-action cushion system and allows for the use of relatively inexpensive forming dies.

3.3 Superplastic Forming Press Design

The traditional process of SPF in which all of the material deformation is controlled by gas pressure simply requires a method of resisting the gas pressure to keep the die closed during forming. Very often, hydraulic presses are used to open and close the die as well as maintain the required pressing tonnage to keep the die sealed. Traditional designs for SPF presses used cartridge heaters in the platens to produce the high-temperature environment. Simple cavity tools are affixed to these platens and are heated through conduction from the platens. In some cases, dies have been equipped with heater cartridges for direct heating rather than conduction from the platens. It has been argued that for higher production volumes, this approach is required to achieve acceptable temperature homogeneity (Ref 21). While this approach offers improved temperature control, it also adds considerably to the cost of the die.

Another key aspect of an SPF press is the gas-management system that controls the forming pressure within the die. These systems need to balance accuracy in achieving a specific pressure within the die with the rate of pressurization. Hence, the valving needs to be sized both to accurately control the pressure within the die cavity and to move a significant amount of gas in a short period of time. Early systems were based on simple solenoid-activated valves to achieve the targeted pressure profile over time. These systems were relatively slow in terms of pressurization and had only moderate control of forming pressure. With the need for faster forming times and improved control, it is necessary to develop methods of moving gas into the die cavity at faster rates without losing accuracy in pressure control. To achieve this improvement, computer-controlled, pneumatically activated, proportional valves have been used to achieve very good accuracy in pressure control while also allowing for the relatively quick movement of forming gas. At Ford Motor Company, a new system was implemented that has excellent control of forming pressure (±7 kPa) and can achieve very fast pressurization rates. Additionally, this new system has been designed to be able to control the gas pressure accurately even with the application of complex gas-pressure cycles.

The press designed and implemented at Ford Motor Company has other unique attributes that are important to the overall development plan. As noted previously, one key aspect of the hybrid process of preforming is the use of a blank holder. To retain the low-investment aspects of the SPF process, it was critical to limit the degree of complexity in the SPF dies. Hence, a new die system was developed (as discussed previously) that used a second action in the press rather than the die (Ref 20). The higher initial investment in the double-action press allows for the use of relatively inexpensive SPF dies that offer a true combination of SPF with stamping.

3.4 Process Simulation

Application of SPF requires the development of simulation tools for process feasibility and die design. To facilitate software compatibility and efficient implementation, finite-element codes have been applied to SPF that are consistent with the suite of computer-aided engineering (CAE) technologies currently in use in the automotive industry. An implicit finite-element analysis (FEA) code has been used to develop a fundamental simulation capability and an explicit code applied to establish a more broad and effective package for commercial product development. Implicit codes use implicit time integration and, thus, are unconditionally stable; their step size is a function of the desired accuracy and computation cost increases per increment. The convergence limitations of the method are often associated with the complexity of contact conditions in forming simulation. In practice, for basic SPF models developed with appropriate constitutive equations and boundary conditions, the solution is reasonable when compared with experiments (Ref 22). Hence, implicit FEA has been found to be suitable for establishing fundamental two- and three-dimensional analysis methods, constitutive behavior, pressure control algorithms, and simulation parameter guidelines (Ref 23-25).

However, the expanded and more demanding requirements of automotive SPF require an FEA capability for simulating large complex geometries and hybrid processes in which SPF is combined with conventional forming operations. Explicit simulation methods are ideal for high-speed impact problems and have been extensively used in vehicle crash simulations. The method is conditionally stable, thus requiring small time steps as imposed by the Courant condition (Ref 26). However, the cost per time step is small for large systems, and there is no equilibrium checking required for convergence. Additionally, adaptive meshing and mass scaling are techniques commonly applied with explicit codes in forming operations and serve to reduce computation time. Care must be taken in explicit simulation especially when applying mass scaling that may adversely affect results. For this reason, an implicit code is used in fundamental SPF correlation and research and serves as the initial benchmark to verify explicit solutions.

An iterative approach has been applied for establishing correlation between experiment and simulation with additional focus on developing superplastic forming die-design guidelines. All SPF dies are developed with simulation support to the extent of current modeling capabilities. Initial forming trials focus on correlating final part thickness and forming time with simulation. These are evaluated, and the FEA model is refined and updated to improve simulation capability and establish predictive limitations. By understanding the capabilities and limitations of SPF FEA, modeling studies can also be applied in developing design guidelines for SPF dies. In this way, SPF technical expertise is derived from simulation as well as experimental trials.

There are many common technological issues in SPF simulation that offer significant opportunity to advance the technology, among them are development of robust constitutive models that provide good thickness and forming time prediction over a wide range of strain rates and temperatures. Additional work must also focus on the development of optimum forming cycle prediction algorithms and failure criterion. Finally, the proper treatment and experimental correlation of frictional effects in SPF modeling remain to be established. These and other simulation advancements will promote the use of superplastic forming by addressing not only manufacturing concerns, but also by establishing reliable up-front feasibility analysis in product development.

3.5 Lubrication

As in other forming operations, friction between the sheet material and the die surface needs to be minimized. In SPF, this is critical since the process is a net-thinning operation with no additional material flowing into the die cavity. While oil-based or waxy lubricants are typical in conventional stamping operations, these types of lubricants cannot withstand the high forming temperatures (400-500 °C) necessary for SPF. Consequently, solid lubricants such as graphite or boron nitride are often used. In addition to lubricants, surface coatings on the tools can be used to further reduce friction (Ref 27). Together, the lubricant and die surface coating minimize the friction between the die surface and the sheet blank. The ability to characterize this friction state is vital to establishing the performance of the different frictional systems (lubricant plus coating) as well as to produce data to be used in CAE simulation of the process.

While there are several conventional methods that can be used to characterize friction at elevated temperature, none of them are appropriate to simulate the SPF process. Tests such as the draw-bead simulator are used in stamping and can be used at high temperature, but are more indicative of a sheet material traversing a draw bead. The SPF process does not use draw-beads, so this type of test is not representative of the process. Another type of frictional test system, which can also be used at elevated temperature, is the pin-on-disk tester. Again, this system does not represent the SPF process. A novel system has been developed at Ford Motor Company based on the type of

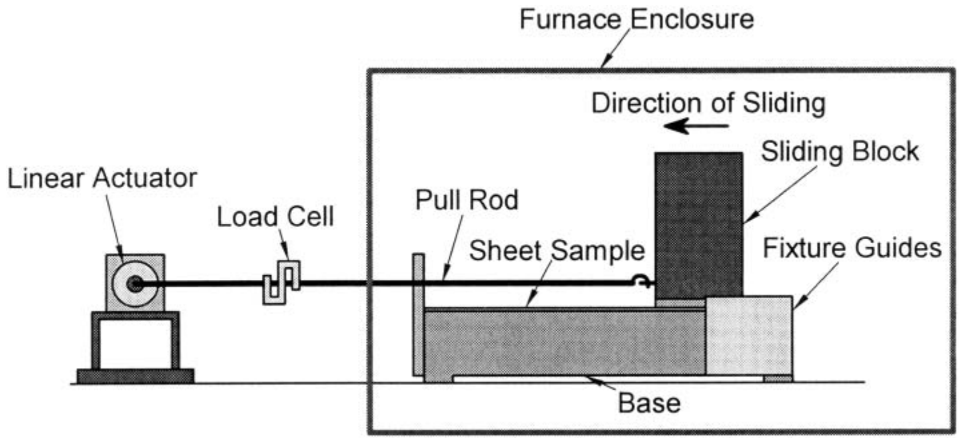

Fig. 5 Schematic illustration of the high-temperature friction testing apparatus developed at Ford Motor Company

sliding friction found in the SPF process and offers a quick and accurate method of determining the performance of both lubricants and coatings.

The new system is based on measuring the force required to pull a test block with a specific surface over a sheet sample. A schematic of the SPF friction test system is shown in Fig. 5. This is reversed from the typical strip draw test, which is based on pulling a test strip between two stationary blocks. At the elevated temperatures of interest, many sheet materials have very low flow loads and therefore deform easily. If the sheet were to deform, the measured loads to move the sheet would be influenced by the deformation in the sheet. The advantage of pulling the block over the sample as opposed to the more conventional strip draw test is that the test material does not deform during the test.

As illustrated in Fig. 5, the system is placed in a furnace equipped with a small hole on the left-hand side. A pull rod attached to the sliding block extended through the hole is connected to a linear actuator that pulls the sliding block. A load cell is located between the two, outside of the furnace, to measure the load as the block is pulled across the sample. The output of the load cell is sent to a signal conditioner and then to a computer to record the load versus time data. This data set can then be used to compare the response of different friction conditions (lubricant and surface). Additionally, the coefficient of friction can be calculated based on this load information and the known pressure the sliding block induces on the test sheet. Data from tests performed at two different temperatures are shown in Fig. 6. The load data are plotted simply as a function of time as the block is pulled across the sheet sample. While there is some scatter in the data, they clearly indicate the superior performance of this lubricant at the higher test temperature.

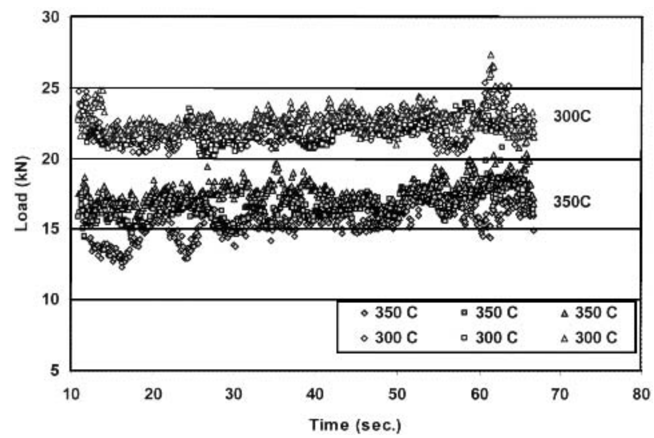

Fig. 6 Example data produced from the friction test system shown in Fig. 5

3.6 SPF Manufacturing Process

The high-temperature aspects of superplastic forming add significant complexity to the manufacturing process and results in several technical challenges. Die cooling during blank loading and part extraction requires time-consuming reheating periods, which lengthen part-to-part cycle time. Within the aerospace industry, several processes have been used to mitigate this issue. One approach is to use induction heating of the material within ceramic dies, thus eliminating the need to heat the dies (Ref 28). Direct electrical resistance heating of the dies has also been used with ceramic dies (Ref 29). While the approaches work well for low-volume applications, durable ceramic tools capable of several thousand parts do not yet exist. Preheating of blanks prior to loading into the SPF dies is considered a vital aspect of shortening the part-to-part cycle time of SPF. Processes using induction, infrared, and conventional radiant preheating systems have all been applied to high-temperature forming operations (Ref 30). After preheating, a suitable loading system is required to move the hot blank into the die. While simple transfer systems or robots can be used to move sheet material, the high temperature adds complexity to the process. The low flow stress of the material at the elevated temperatures also requires that the sheet be supported during the loading process. Additionally, it is important that the transfer of the blank from the preheat system to the die is relatively quick so that significant heat is not lost from the blank.

For low-volume products, parts are removed from the press manually. However, for the higher production volumes of the automotive industry, rapid and efficient unloading of the part is essential to achieving acceptable production cycle times. The high temperature of the blank coupled with the fact that it has conformed to the die shape under pressure, can make it difficult to remove the part. In low-volume production, dies are often designed with access for pry bars to help remove parts. While several processes to facilitate part removal have been listed in the patent literature, most of these are not suitable for higher-volume automotive parts (Ref 31-33). New processes have been developed that may offer a better fit to the faster cycle times needed in automotive production (Ref 34-36). A new system has been developed at Ford Motor Company that is based on the difference in thermal expansion/contraction between the steel die and aluminum sheet. This system acts both to remove the sheet from the forming die and to help prevent warping of the part as it cools.

4. Summary and Conclusions

Superplastic forming is a high-temperature forming process than can significantly expand the forming limits of aluminum sheet. This low-investment process has been used extensively in the aerospace and rail industries due to their low volumes and, therefore, the need to limit tooling costs. To date, application of this process to the automotive industry has been limited due to the cost penalty of materials specially processed for superplastic forming coupled with relatively long forming times. However, recent technological developments in both materials and manufacturing indicate it may be possible to increase the production volumes for which SPF is a cost-effective solution. Developing a complete manufacturing strategy, including up- and downstream processes, is a key step in integrating SPF within the automotive production process.

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