JMEPEG (2010) 19:495–502
DOI: 10.1007/s11665-010-9616-2

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1059-9495/$19.00

Finite Element Modeling, Simulation, Tools, and Capabilities at Superform

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(Submitted December 9, 2009; in revised form January 7, 2010)

Over the past thirty years Superform has been a pioneer in the SPF arena, having developed a keen understanding of the process and a range of unique forming techniques to meet varying market needs. Superform's high-profile list of customers includes Boeing, Airbus, Aston Martin, Ford, and Rolls Royce. One of the more recent additions to Superform's technical know-how is finite element modeling and simulation. Finite element modeling is a powerful numerical technique which when applied to SPF provides a host of benefits including accurate prediction of strain levels in a part, presence of wrinkles and predicting pressure cycles optimized for time and part thickness. This paper outlines a brief history of finite element modeling applied to SPF and then reviews some of the modeling tools and techniques that Superform have applied and continue to do so to successfully superplastically form complex-shaped parts. The advantages of employing modeling at the design stage are discussed and illustrated with real-world examples.

Keywords 5083-SP, aluminum, automotive, superplastic

1. Brief History

The history of superplasticity has been extremely well documented in publications such as Ref 1. The history dates back to as early as 300 B.C. when Damascus Steel was used in sword making (Ref 2). The works of Bengough, Jenkins, and Pearson make up the earliest recorded reports of superplasticity (Ref 1). The work done by Bochvar and Sviderskaya in 1947 and a review of the same by Underwood in 1962 (Ref 3) fanned the flames of research relating to Superplasticity in the west. The experiments at MIT in 1964 by Backofen et al. with the Zn-Al eutectoid and their comments in their paper (Ref 4), where they saw potential in borrowing forming techniques from glass and polymer processing and applying them to superplastic metals inspired Dr. Davis Fields to pursue ideas along these lines at IBM research labs (Ref 5). The events during the year 1969 including the now famous issue of Design Engineering with SPF as the 'cover story', the first dilute aluminum alloys at Tube Investments (TI) Research Labs in the United Kingdom, and the birth of Superform have been documented in Ref 5. The collection of images shown in Fig. 1 illustrates chronologically the turning events in the history of superplastic forming.

This article is based on a presentation at the AeroMat Conference, International Symposium on Superplasticity and Superplastic Forming (SPF) held in Austin, TX, June 23-26, 2008.

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2. Early Part Forming and Methods at Superform

Since its inception in 1974, Superform has been making aluminum sheet metal components with extremely complicated shapes. An array of different parts made through the years at Superform is shown in Fig. 2. Shapes like the Martin-Baker ejector seat head-rests (top left in Fig. 2) are complicated and still would represent quite a challenge today even with all the computer-aided tools and modeling techniques that are available to engineers. The question then is "How was it done?" The answer lies in the early notes and analysis of A.J. Barnes at Superform, plotting graphs and finding empirical relationships based on data from forming trials. These were later written up in a more comprehensive manner as 'Superform Manuals', which were used as constant reference during tool design. An excerpt from one of the volumes of the Superform Manuals is shown in Fig. 3.

The empirical relationships that were derived were based on a number of assumptions, e.g. sticking friction assumption meant that the material would not undergo further strain after it had contacted the tool surface or the assumption of a perfectly hemispherical bulge and so on. Whenever a set of mathematical equations based on a set of assumptions is used to describe a process within reasonable limits, we refer to it as a process model.

3. Process Models

Process models are mainly of two types: physical and computational (Ref 6). A process model can also be derived based on trial and error where enough data points are obtained to develop models like those in the Superform Manuals. Figure 4 shows the different types of process models.

3.1 Physical Models

Physical models include Chandra's idea of a Plexiglas mold and vacuum forming a thin sheet of elastomer to visualize

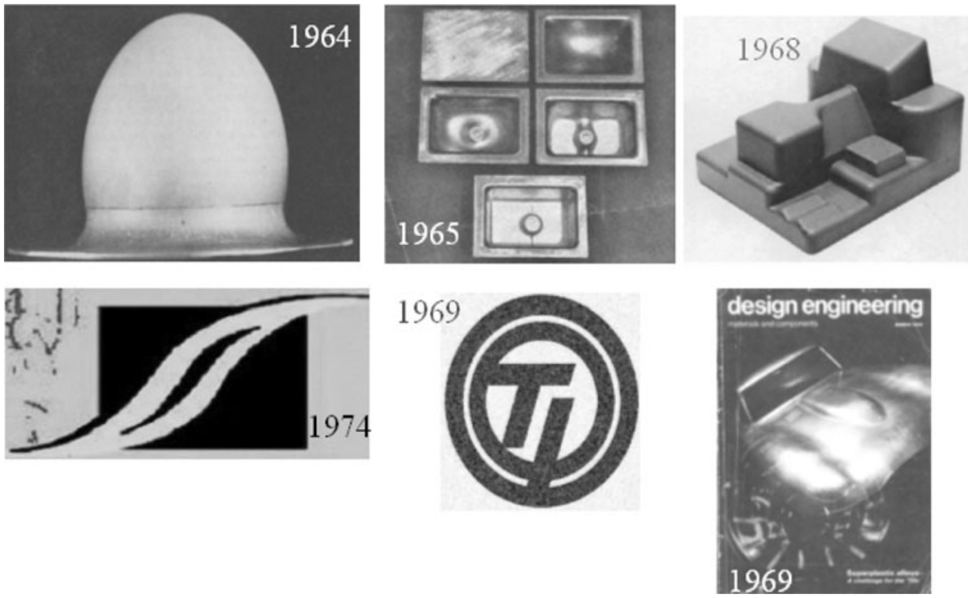

Fig. 1 A pictorial chain of key historical events showing Prof. Backoven's ZN-Al superplastic bubble (1964), experimental parts at IBM (1965), a complicated part made from Zn-Al eutectoid at IBM (1968), the cover of Design Engineering (1969), and the subsequent involvement of TI and the birth of Superform (1974) shown by their respective logos (Ref 5)

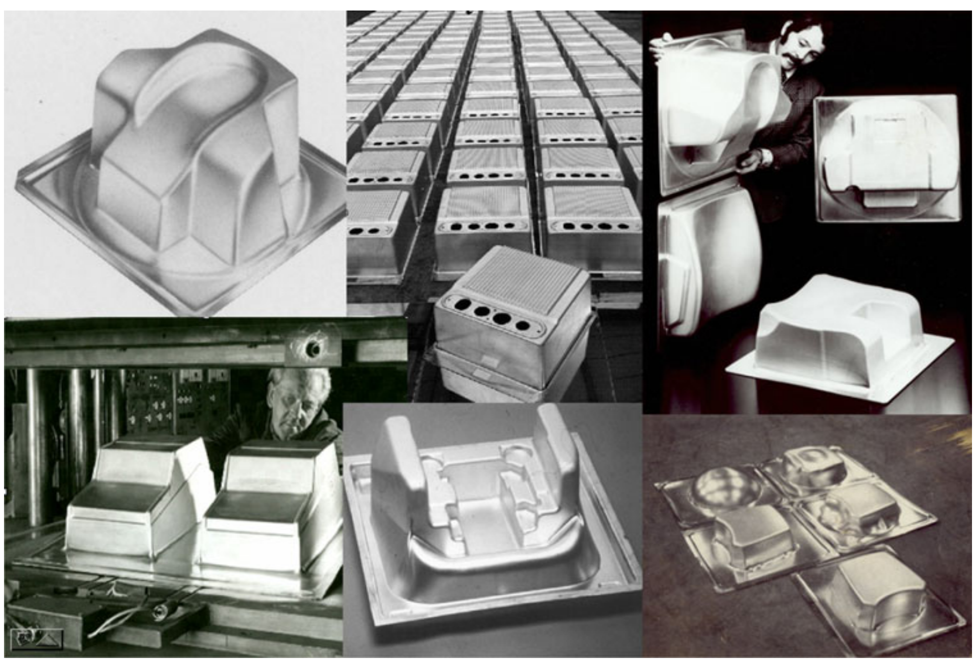

Fig. 2 Examples of superplastic aluminum alloys formed into various complicated shaped components for a variety of applications at Superform

wrinkles and get a feel for material behavior (Ref 6). Another example of physical modeling is making a quarter scale model of the tool design out of foam, draping a sheet of plastic over it to mimic the material and adding features on the tool based on what is observed. This method has been followed at Superform for many years now. Figure 5 shows one such quarter scale tool design.

3.2 Computational Models

Computational models attempt to describe the process using mathematical equations ranging from simple to extremely complex and a set of assumptions. Chandra further divided computational models into 'simplified', 'numerical', and 'finite element'. Simplified models, as the name suggests, represent

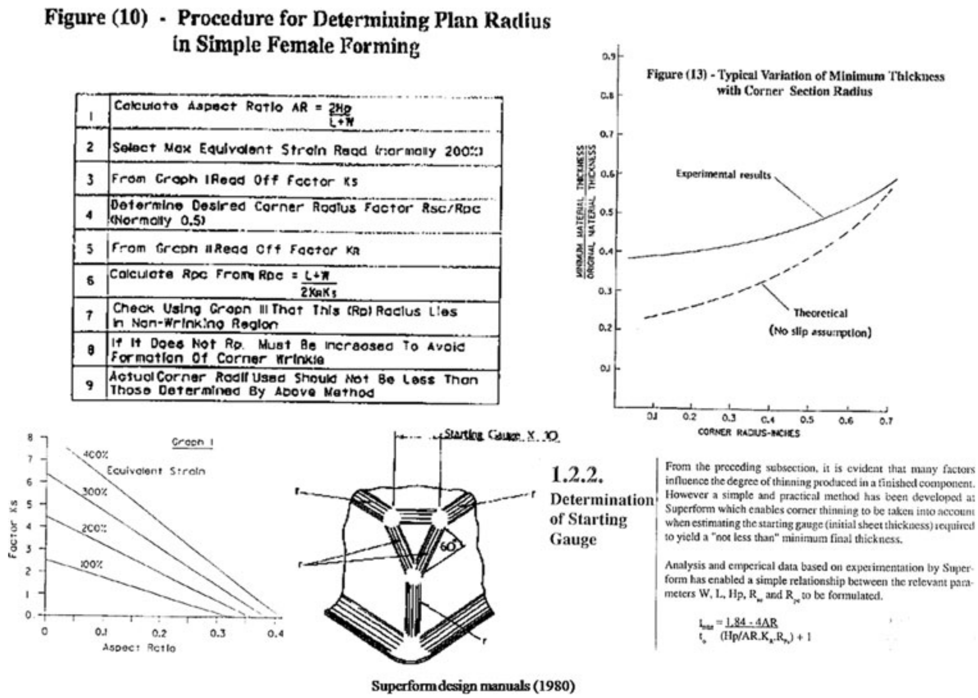

Fig. 3 An excerpt from the Superform Manuals showing one of many plots derived from empirical data that were used to determine key parameters during the design process

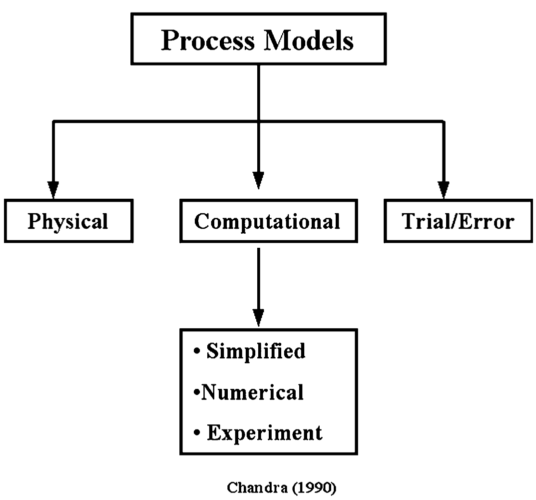

Fig. 4 Different types of SPF process models (Ref 6)

the process in a really simplified form. Assumptions such as conditions of plane strain, simple shapes during the various stages of deformation, and 'no-slip' are common. For a detailed analysis of this type of process model, refer Ref 6.

Numerical models are a little more complex compared to simplified models. Here, separate equations are used for accounting for non-uniform thinning. Usually, the problem is simplified as a 2D section and the sheet is discretized into a few elements and the elemental results are calculated at different points in time and assembled to give the global result. Refer Ref 7 for a detailed analysis of SPF using membrane element method. The inability to model the problem in its entirety and

Fig. 5 A form tool for an automotive component is designed using a quarter scale 'Physical Model'

the simplified nature of these models severely limited their utility when it came to modeling SPF of complicated parts. The Finite Element Method was the solution to the problem.

4. Finite Element Method

Numerical analysis of engineering problems, primarily finding solutions for equations of plasticity, date back to the early 1900s. In the 1930s, Southwell's method of 'systematic relaxation of constraints' was used widely to solve problems relating to structures. Dr. Olgierd Zienkiewicz, who was one of the earliest contributors to the advancement of FE methods, likened Southwell's relaxation technique to the Gauss-Siedel iteration method that is used in iteratively solving a system of linear equations (Ref 8). This method of systematically solving

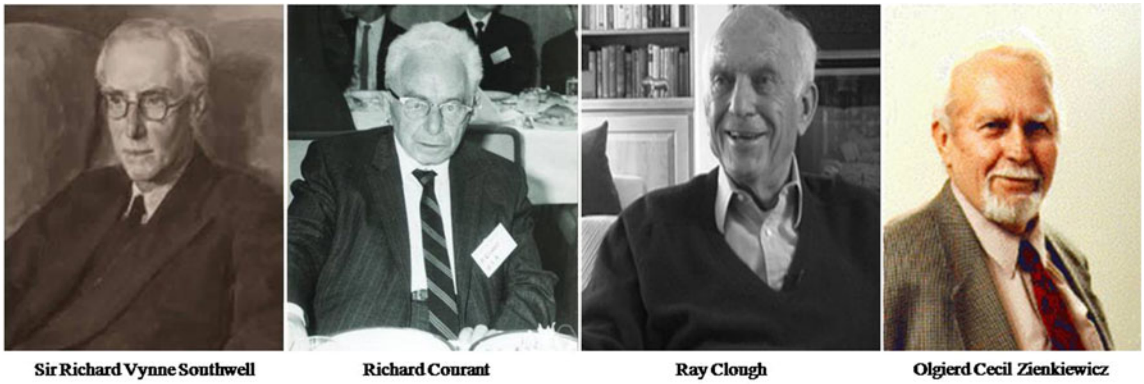

Fig. 6 Early pioneers of FE methods: Southwell, Courant, Zienkiewicz, and Clough

for nodal solutions by relaxing constraints in a system found favor among engineers as they liked the way the method physically interpreted the system and simplified boundary conditions (Ref 8). However, the birth of FE methods as we know them today is said to be a written lecture by Courant to the American Mathematical Society, where he determined the torsional rigidity of a shaft by splitting the continuum into triangles and using linear stress interpolation function over each triangle from nodal values (Ref 9). In a paper in 1960, Ray Clough, another early pioneer of finite element methods, actually coined the term 'Finite Element' (Ref 8). Since matrix calculations and inversions that were performed in a typical FE problem were easily programmable, the use of computers was almost inevitable. Early FEA was severely limited by computational power available then and required analysts to perform multiple runs of different sections of a problem. Today, there is no perceivable limit on the amount of computing horsepower that can be brought to bear on the problem and with very advanced codes tailor-made for specific applications; FEA has become an absolute necessity in nearly every field of engineering. A collection of photographs of these early pioneers of FEA is shown in Fig. 6.

Modern FE codes have been made very much more user-friendly than in the past. Graphic-user interfaces and problem set-up are now quick and easy. While this is a great advantage, it also gives a false impression that someone without a fundamental understanding of FEA can perform analyses. It is critical to understand that, while FEA is a very powerful tool, the results that are generated are only as good as the numbers that are put into the code. So without a thorough understanding of the basics of FEA, the results obtained can be anywhere between embarrassing and disastrous (Ref 9).

4.1 Explicit and Implicit FEA

Metal forming operations like SPF fall under a category known as large deformation problems that are time dependent. They can be represented by Newton's second law written in matrix form as shown in Eq 1. The solution is obtained by integrating the equation over time referred to as Direct Integration (Ref 9)

$$[M]\{\ddot{D}\}_n + [C]\{\dot{D}\}_n + \{R^{\text{int}}\}_n = \{R^{\text{ext}}\}_n \qquad \text{(Eq 1)}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, and $[D]$ is the displacement matrix. $[R]^{\text{int}}$ and $[R]^{\text{ext}}$ are internal and external force matrices, respectively. The equation gives the response of the system at time step 'n'. Direct integration is used to calculate response at time $n + 1$ from the equation of motion, a difference expression and conditions from prior time steps (Ref 9). The integration algorithms are of two types: Implicit and Explicit.

Implicit FEA has a difference expression given by Eq 2. The difference expression has conditions of state from prior time steps as well as the current time step. Conditions of static equilibrium are imposed on the current time step making the method unconditionally stable. Implicit FEA is computationally very intensive and is more suited to systems exhibiting low deformation and high intrinsic stiffness, e.g. structures.

The difference expression for explicit FEA is given by Eq 3. The expression has terms relating only to prior time steps. Since conditions of static equilibrium are not sought at the current time step, explicit direct integration is conditionally stable as governed by the CFL criterion. For a detailed analysis of these two types of direct integration, refer Ref 9, 10. Explicit FEA is computationally less intensive, is more suited to large deformation problems like SPF but its stability is dictated by the size of the time step. Techniques like mass scaling are often employed in explicit codes to increase time step size by artificially scaling the mass of the material, taking great care not to influence the results. For a detailed explanation of mass scaling in explicit FEA and potential pitfalls associated with it, refer Ref 11.

$$\{D\}_{n+1} = f(\{\dot{D}\}_{n+1}, \{\ddot{D}\}_{n+1}, \{D\}_n, \{\dot{D}\}_n\{\ddot{D}\}_n, \ldots) \qquad \text{(Eq 2)}$$

$$\{D\}_{n+1} = f(\{D\}_n, \{\dot{D}\}_n, \{\ddot{D}\}_n, \{D\}_{n+1}, \ldots) \qquad \text{(Eq 3)}$$

5. FEA Applied to SPF

Finite element analysis of SPF usually involves the following; the creation of a robust CAD model of the prototype tool, a material model to describe the behavior of the material, means to apply constraints, a known pressure cycle or an algorithm to predict one based on a target strain rate and a method to post process the results. An accurate material model is extremely important for the results to actually get close to reality. There are a number of different material models that have been published which capture various microstructural events with a number of parameters (Ref 12). Most of these are either too complex to input into the code or there is just not enough data to come up with accurate parameters. The most widely used material model to model superplastic materials is the simple power law given by Eq 4, which has proved to be pretty robust in terms of capturing the behavior of most superplastic materials and can be used to model superplastic forming (Ref 5).

$$\sigma = K\dot{\varepsilon}^m \quad \text{(Eq 4)}$$

Some early work done in finite element modeling includes the efforts by Bonet, Wood, and Zienkiewicz, where the forming of a truncated ellipsoid with a spherical indent was modeled. The results included an optimum pressure cycle for a target strain rate and thickness of the forming (Ref 13). Since then, work has been done on each aspect of the finite element model, namely, material models (Ref 12), pressure prediction (Ref 14, 15), and special element formulations suited for SPF (Ref 16). Research and development efforts continue to this day in these areas.

6. Modeling Capabilities at Superform

At Superform, making complicated shapes is nothing new, so the introduction of finite element modeling cannot be completely credited with the ability to take on challenging geometries and successfully 'Superforming' them. What it does allow is a high level of confidence when the time comes to create the actual form tool. A typical design cycle is shown in Fig. 7. It is important at this point to understand that there is no software that automatically designs the tool. The tool is always designed by the engineer and is iteratively improved based on the results from modeling.

The FE code of choice at Superform is PAMSTAMP-2G, which is a commercially available explicit code primarily developed for stamping. The version used for SPF, however, has unique modules tailor-made for the process. The software is capable of automatic meshing of tool geometry, adaptive meshing of blank elements, the capability to scale sheet velocity and mass and an algorithm to predict a pressure cycle for a part. The code has been put to use to refine tool designs for complex parts, optimizing thickness and forming time. The following section will deal with two case studies where finite element modeling has been put to two different uses; one to optimize tool design for a new part and the other to overcome a subtle surface defect in an existing part.

7. Case Studies

7.1 Case Study 1: Airstair

The airstair is actually small fleet of four steps that is integrated to the door of a small aircraft. Superform proposed a design to replace a 23-piece weldment thereby offering a lighter, stiffer, and cost-effective solution to the customer. Superform's one-piece design is compared to the original design in Fig. 8.

The new design incorporated smooth radii and truncated corners to minimize localized thinning and eliminate possible failure. Several design iterations were performed before the final design was arrived at as shown in Fig. 9.

To achieve optimized thicknesses on the part, a novel two-stage forming process was used. The heated flat sheet was superplastically pre-stretched in certain regions before being

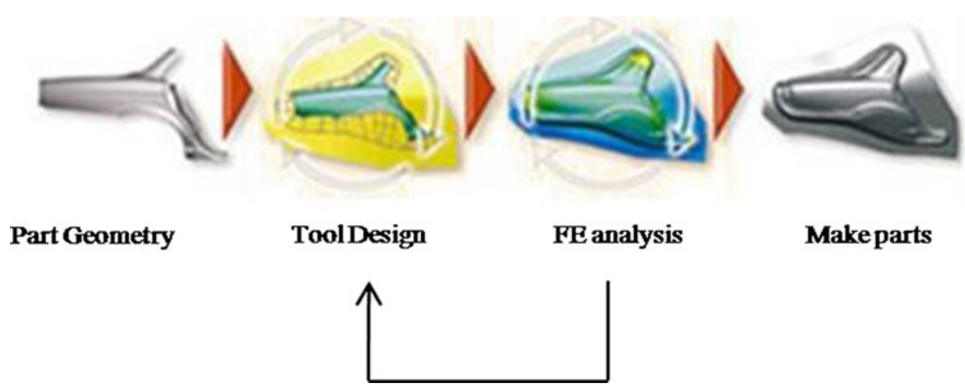

Fig. 7 Typical design cycle involved in successful forming of a part (thumbnails courtesy ESI NA)

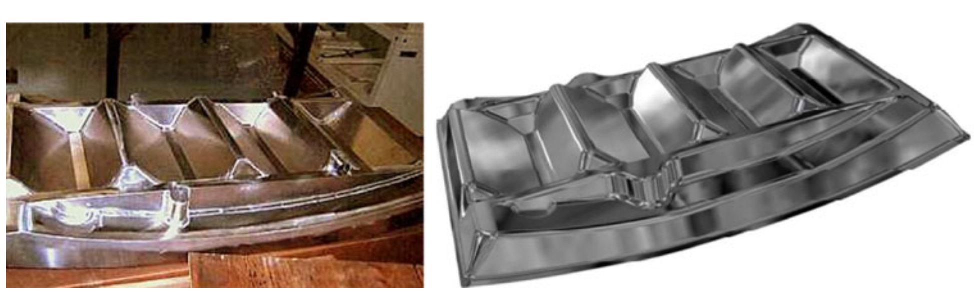

Fig. 8 The original design, a 23-piece weldment in comparison with the proposed one-piece design

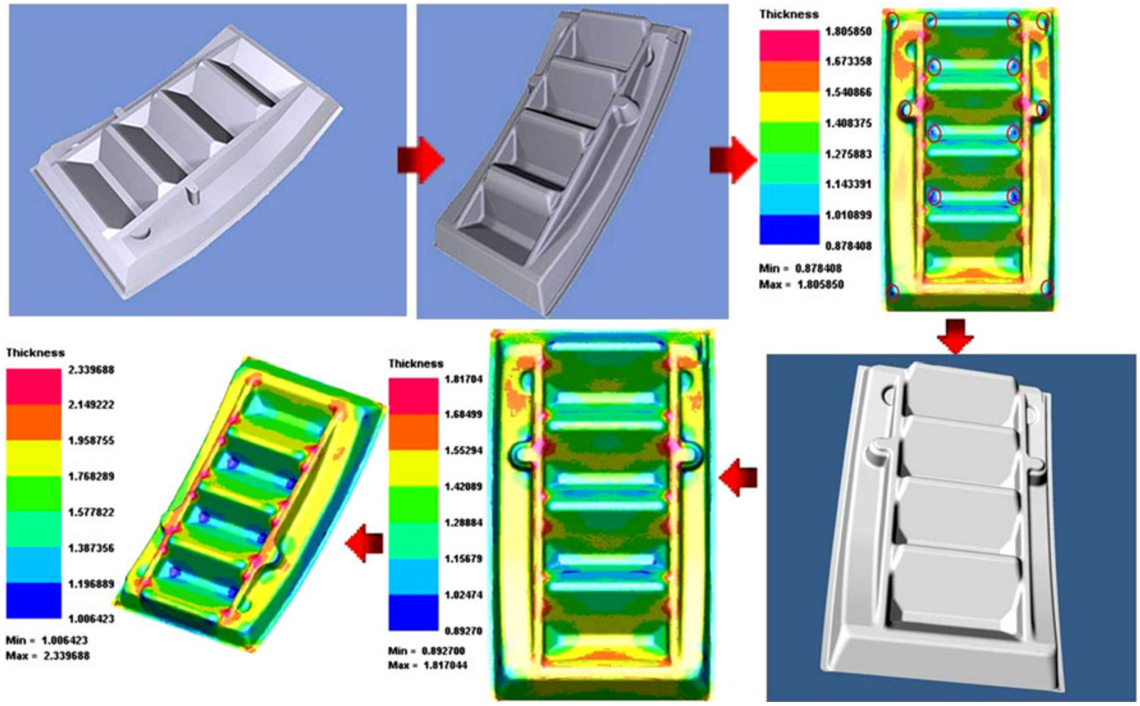

Fig. 9 Different stages in the design iteration process leads to a design optimized for SPF

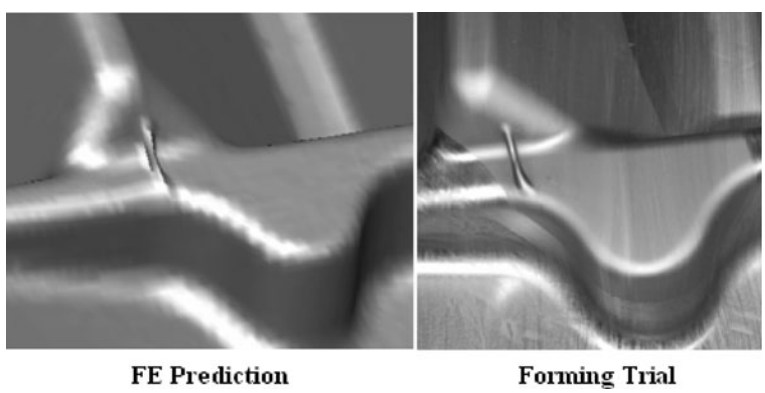

Fig. 10 Remarkable correlation between simulated and actual wrinkle resulting from excessive pre-stretching

draped over the tool surface to create the final shape; all this being carried out in a single press cycle. The pre-stretching step is critical, if over-stretched, simulation predicted a wrinkle. Figure 10 illustrates the simulated wrinkle and the actual wrinkle created when the pre-stretching was overdone. The finished part is shown in Fig. 11.

7.2 Case Study 2: Truck Bumper

One of many components that are superplastically formed for the trucking industry at Superform is a one-piece bumper almost 9 feet in length that ends up as a polished and chrome-plated component on the new International Lonestar truck. A picture of the truck with the bumper in situ is shown in Fig. 12.

The tool design for the bumper was optimized by extensive finite element modeling. The surface quality of the formed panel is critical in this case because even a slight imperfection will show up after polishing and chrome plating. In this case, two circular surface aberrations were noticed at symmetrical locations on the bumper (see Fig. 13). These aberrations were 'optical flaws', where a small variation in local thickness changes the way the surface reflects light compared to surfaces surrounding it.

The unique ability to 'see inside the press' by modeling the forming process enabled a solution to this problem to be virtually tested before committing to hardware changes. In this case, a certain degree of mechanical pre-forming was employed during the die-closeout in order to achieve optimized part thickness. The shape of the sheet just after die closeout is shown in Fig. 14.

As the gas pressure comes on to form the part over the tool, the material within the encircled region comes close together to

Fig. 11 Airstair—finished product

Fig. 12 Polished bumper in situ on the truck

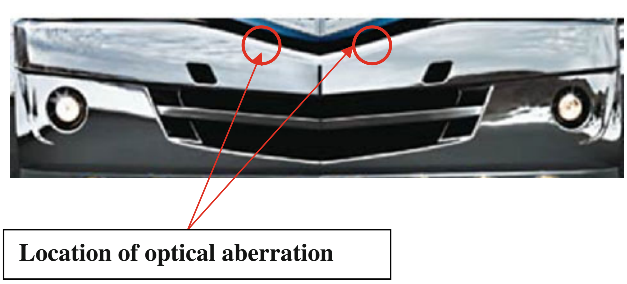

Fig. 13 Locations of the 'optical aberrations' on the bumper

form a wrinkle but subsequently is pulled out as the forming is completed. As the wrinkle is pulled out, it leaves a very slight variation in local thickness, of no more than a couple of thousands of an inch, resulting in an optical aberration.

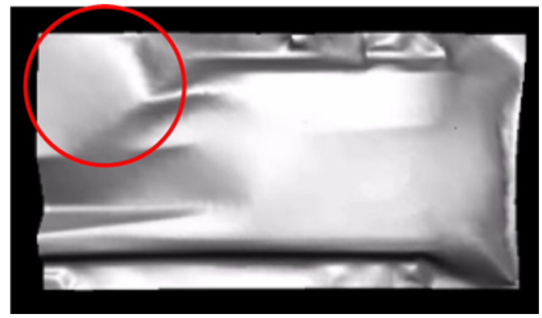

Fig. 14 Snapshot from FE simulation showing the shape of the sheet after die closeout

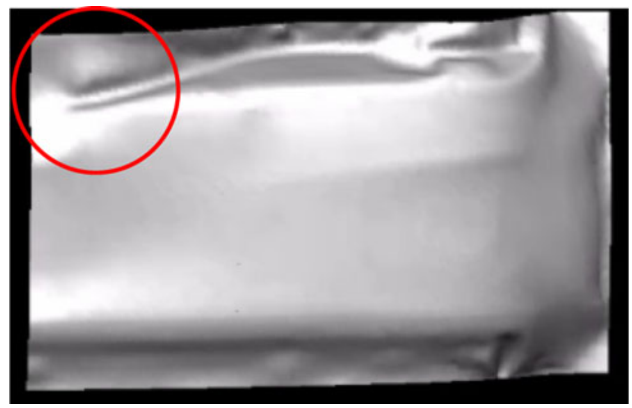

Fig. 15 Snapshot from FE simulation showing the altered shape of the sheet after die closeout

Using modeling, the mechanical performing hardware was altered to change the shape of the sheet after die closeout. The resulting preformed shape in Fig. 15.

The material within the encircled region looks remarkably different compared to Fig. 14. When the gas pressure comes on, the dynamics of the forming have been sufficiently altered and the wrinkle that originally formed is completely eliminated. These changes were then incorporated in the tool and the result was a part that was completely free of problematic optical aberrations.

This problem is a classic example that shows that modeling, when executed correctly, can capture subtle details occurring during forming and can be used to solve problems requiring equally subtle solutions.

8. Concluding Remarks

While modeling is a very powerful tool, its full potential is realized only when used with a combination of sound engineering principles and an innovative outlook. It is imperative to understand that modeling is an engineering aid and can never replace good engineering. The FE analyst must always question the accuracy of the results generated. In cases where modeling and reality do not match, every effort must be taken to understand the reasons behind the discrepancy. To conclude, when modeling is used in synergy with lessons learned from experience, the result is a fascinating journey continuing onwards and upwards in the ever intriguing realm of superplasticity.

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