PRODUCT, TOOL, AND PROCESS DESIGN METHODOLOGY FOR
DEEP DRAWING AND STAMPING OF SHEET METAL PARTS

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the
Graduate School of The Ohio State University

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* * * * *

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"But neither politics nor ethics nor philosophy [nor science] is an end in itself, neither in life nor in literature. Only Man is an end in himself."

- Ayn Rand, The Goal of My Writing, Lewis and Clark College, October 1, 1963
ABSTRACT

More powerful sheet metal forming design tools are needed to help engineers design better products and processes, to reduce lead times and costs, and to increase product performance and accuracy. With these issues in mind, the objectives of this dissertation are:

- To develop a part and process design methodology for the deep drawing and stamping of sheet metal parts.
- To generate computerized tools to aid engineers on the use of this proposed design methodology.

The scope of this dissertation consists of:

- Sheet metal parts ranging from cylindrical shells to complex automotive body panels.
- Materials ranging from drawing quality steel, high strength steel, dent resistant steel, and aluminum alloys (2000, 3000, 5000, and 6000 series).

The major research contributions and technologies that are associated with this dissertation are:

- A mathematical model and computer software that allows engineers to calculate forming forces, formability limits, required tool geometry, and optimal process conditions (BHF profiles) for simple part geometries such as round cups, rectangular pans, U-channels, hemispherical shells, and asymmetric panels.
- A module for commercial finite element method (FEM) programs that implements a feedback loop into the calculations (adaptive simulation) in order to
determine optimal process conditions (BHF profiles) for general complex geometries.

- Computerized tools that provide engineers with the effect of process parameters on part quality (sensitivity data) for various simple laboratory tool geometries using laboratory experiments and computer simulations.

The prediction of optimal process parameters will focus primarily on determining the optimum time and spatial variation of the blank holder force (BHF) given a particular geometry. It has been proven in laboratories that drawability can be improved by changing the blank holder force during the stroke of the press (i.e., during deformation). Also, it has been observed that part quality can be enhanced by modifying the distribution of blank holder pressure (BHP) around the periphery of the blank. Thus, the question becomes given a certain geometry what is the optimum spatial distribution and time variation of the BHF? It is the goal of this work to contribute towards answering this question.
For my wife and newborn son ~
Laura and Ethan

∞ ∞ ∞ ∞ ∞

Vous êtes en mon coeur ...
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### Nomenclature

**Round Cups**
- h = cup height
- d₀ = initial blank diameter
- r₀ = initial blank radius (d₀/2)
- d₁ = inner cup diameter
- r₁ = inner cup radius (d₁/2)
- t₀ = initial cup thickness
- dₘ = mean cup diameter = d₁ + t₀
- f = flange length
- dₙ = instantaneous flange diameter
- rₙ = die radius
- rₚ = punch radius
- dₚ = punch diameter
- dₜ = die diameter
- c = punch/die clearance
- α = wrap angle around die radius
- σᵣ = mean flow stress in the flange
- σₙ = mean flow stress over the die radius
- σₘ = mean flow stress in the wall
- Fₛ = drawing load
- Fₜ, Mₜ, σₜ, Wₜ = Bending force, moment, stress, and work

**Process Parameters**
- Fₜ = blank holder force
- pₜ = blank holder pressure
- Fₜ = fracture load
- μ = coefficient of friction
- kₚ, kᵢ, kₖ = proportional control constants
- η = efficiency factor
- " = inch

**Rectangular Pans**
- w₀ = blank width
- w₁ = pan width
- l₀ = blank length
- l₁ = pan length
- r₀ = blank radius
- r₁ = corner radius of punch
- xᵢ = distance of each cylinder i
- xᵢj = distance between cylinders i, j
- rᵢ = relative distance of each cylinder i
- Fᵢ = force of each cylinder i
- rₑ = effective range
- fₑ = coupling factor
Flow Stress

\( \bar{\sigma} = K[\varepsilon_0 + \bar{\varepsilon}]^n \) = flow stress equation

\( \bar{\sigma} \) = flow stress or equivalent stress

K = strength coefficient

\( \varepsilon_0 \) = prestrain

\( \bar{\varepsilon} \) = true strain

n = strain hardening exponent

M = Hill’s non-quadratic parameter

\( S_y \) = yield strength

\( S_u \) = ultimate strength

\( \sigma_u, \varepsilon_u \) = ultimate tensile stress and strain

\( \sigma_x, \sigma_y, \sigma_z \) = normal stress X,Y,Z-direction

\( \varepsilon_x, \varepsilon_y, \varepsilon_z \) = normal strain X,Y,Z-direction

\( \sigma_1, \sigma_2, \sigma_3 \) = principal stresses

\( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) = principal strains

\( \sigma_r, \sigma_t \) = normal stress radial, tangential, direction

\( \tau_{xy} \) = shear stress in the xy plane

\( r_0, r_{45}, r_{90} \) = anisotropy in 0°, 45°, 90° to rolling direction

\( \bar{r} \) = normal anisotropy

\( \Delta r \) = planar anisotropy

C = critical damage value

\( \eta \) = efficiency factor

\( R_a \) = surface roughness measurement

Acronyms

AKDQ = aluminum killed draw quality

BHF = blank holder force

BHP = blank holder pressure

CAD = computer aided design

DR = draw ratio

ERC/NSM - Engineering Research Center for Net Shape Manufacturing

FDM = finite difference method

FDM = fused deposition modeling

FEM = finite element method

FLC = forming limit curve

FLD = forming limit diagram

LDR = limiting draw ratio

NC = numerically controlled

NZS - Near Zero Stamping

PID = proportional, integral, derivative

STL = stereolithography

VPF = viscous pressure forming
PREFACE

The low gasoline prices will not be enjoyed by the automotive industry indefinitely. When gas prices go up, customers will be looking for more fuel efficient cars and government regulations will become tighter. Among all the methods to increase efficiency, weight reduction is by far the most effective. There are only two methods to reduce weight - optimizing the design and changing the material. Aluminum is a good candidate for weight reduction along with high strength steel and tailor welded blanks. When compared to draw quality steel, aluminum has only one-third the density, a higher strength to weight ratio, and has the potential to reduce the frame and body weight of an automobile by 40-45% (McVay, 1998).

High strength steel has a higher strength and equivalent density when compared to draw quality steel thus provides for good weight reduction. Tailor welded blanks offer the designer greater possibility of designing products with varying thickness and materials. This allows the designer to put strength in the product where necessary and take it out when unnecessary.

The problematic issue within all this is that these low weight materials also suffer from reduced formability when compared to draw quality steel. This situation puts a heavy burden on new technologies and research. In particular, two technologies are at the forefront of making the greatest impact on light weight less formable materials. The first is blank holder force (BHF) control. This technology promises to increase the formability of a material through high precision control of the process.
The second technology is computer simulation. Predictive software can optimize the product, tool, and process before any metal is cut thus increasing the available forming range and process robustness. Both of these technologies are commercially available, which thus leads to the question, what is the next step for researchers?

It is our belief that blank holder force control, albeit very effective, tends to increase the number of process parameters that must be set by the press operator. Furthermore, computer simulations, although accurate, inherently force the user to trial and error tactics. Automatic predictive tools must be developed to provide an educated guess at how to initially set sophisticated BHF control systems. Computer simulation codes must be adapted to provide for this prediction capability without trial and error.

It is the goal of this dissertation to develop the next level of computer simulation - namely Adaptive Simulation.
I would like to make one comment on the quote on the frontispiece of this dissertation. I believe it is dreadfully important for all those who endeavor to complete works of immense effort to maintain some kind of perspective on their lives. In particular, one must put his or her work in context within the great scheme of things. I believe Ayn Rand put it best with this quote:

"But neither politics nor ethics nor philosophy [nor science] is an end in itself, neither in life nor in literature. Only Man is an end in himself."

- Ayn Rand, The Goal of My Writing, Lewis and Clark College, October 1, 1963

Ayn Rand provided this in answer to the question, "Was the Fountainhead written for the purpose of presenting your philosophy on life - Objectivism?" The Fountainhead is a good reference, because the main character is Howard Roark an architect who loves functionality over esthetics, not unlike an engineer. Objectivism is to ethics as capitalism is the economics. This ideal is captured in her book of essays, The Virtue of Selfishness. The title just screams contradiction, but is in fact quite important. Ayn Rand was an immigrated Russian who suffered within the socialist/communist system. I find this to be an interesting point in fact in response to her beliefs. Furthermore, her faculty and precision over the English language, albeit her second language, is astounding - a true intellectual, no question.

Although, Ayn Rand's quote is in response to the above question, she does not waste the answer and is more profound than necessary. In her response, we find that she is a humanist above all else including her writing. She never loses her perspective despite her deep convictions and her desire to document them in essays, fiction, and drama. Ayn Rand reminds us all that we must put the ones we love including ourselves at highest priority. My hat's off to Ms. Rand for guiding me through this difficult task and helping me to not forget what is important.
CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

1.1 Introduction

1.1.1 Classification of Sheet Metal Forming Processes

Sheet metal forming can be divided into three main types of deformation processes - bending, stretching, and deep drawing. Bending, which is the most common type of deformation, occurs in almost all sheet forming operations. Typical bending processes consist of air bending (Figure 1.1), flanging, hemming, and roll forming. Bending processes are characterized by an applied moment or a system of forces which apply a moment to the sheet. The bend zone experiences localized strains which are tensile on the outside of the neutral axis and compressive on the inside.

Stretching is characterized by biaxial tensile stresses. Stretching processes include the plane strain tensile test, hydraulic bulging test and limiting dome height test (Figure 1.2). Stretching is a more global deformation process than bending. Stretching is also the most preferred deformation mode of sheet, because the strains tend to be more uniform and the final product properties are very desirable (such as good stiffness and low springback). The absence of compressive stresses ensures that the sheet does not buckle and maintains good dimensional accuracy of the product. Due to the nature of this process, there will be a net thinning of the final product.

Deep drawing is characterized by tensile/compressive stresses. Classical deep drawing (Figure 1.3) is the process of reducing a blank of diameter $d_0$ to a cup of diameter $d_1$ using a punch to deform the sheet into a die cavity. The primary deformation zone
occurs in the flange of the deforming cup which is undergoing radial tension and circumferential compression. The secondary deformation zone is the bending around the die radius while the tertiary deformation zone is the stretching in the cup wall. Since deep drawing is a combination of all three deformation modes, it becomes a relatively complex process to analyze. Further, there is little net thinning in the final product due to the combination of deformation modes. Cylindrical or prismatic cups, with or without a flange and complex automotive parts, can be produced with this process.

Figure 1.1: Air bending (Livatyali, 1998)

Figure 1.2: Stretch forming (Crowley, 1998)

Figure 1.3: Classical deep drawing
1.1.2 Sheet Metal Forming as a System

A sheet metal forming system takes into account all process parameters such as the blank (geometry, material), the tooling (geometry, material), the conditions at the tool/material interface (lubricant, surface finish), the mechanics of plastic deformation (plasticity), the equipment (stroke rate, ram velocity), the product quality and functionality requirements, and finally the plant environment where the process is being conducted (Altan, 1983). The application of the systems approach to sheet metal forming is illustrated in Figure 1.4 as applied to deep drawing.

The systems approach to sheet metal forming allows study of the input/output relationships and the effects of process variables on product quality and process economics. To obtain the desired shape and properties in the product, the metal flow should be well understood and controlled. The direction of flow, the magnitude of deformation, and the temperature involved greatly influence the properties of formed products (Altan, 1983). The effect of process variables on such product quality issues as fracture tendency, wrinkling tendency, and springback has been classified by the author of this proposal are shown in Table 1.1.

Figure 1.4: Sheet forming as a system
<table>
<thead>
<tr>
<th></th>
<th>FRACTURE</th>
<th>WRINKLING</th>
<th>SPRINGBACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank Holder Force (BHF)</td>
<td>direct</td>
<td>inverse</td>
<td>inverse</td>
</tr>
<tr>
<td>Blank Size</td>
<td>direct</td>
<td>direct</td>
<td>direct</td>
</tr>
<tr>
<td>Sheet/Binder Friction ($\mu_{sb}$)</td>
<td>direct</td>
<td>inverse</td>
<td>inverse</td>
</tr>
<tr>
<td>Sheet/Punch Friction ($\mu_{sp}$)</td>
<td>inverse</td>
<td>inverse</td>
<td>non-linear</td>
</tr>
<tr>
<td>Thickness Homogeneity ($\Delta t$)</td>
<td>inverse</td>
<td>inverse</td>
<td>inverse</td>
</tr>
<tr>
<td>Nominal Thickness ($t$)</td>
<td>non-linear</td>
<td>inverse</td>
<td>inverse</td>
</tr>
<tr>
<td>Normal Anisotropy ($\bar{\tau}$)</td>
<td>inverse</td>
<td>inverse</td>
<td>direct</td>
</tr>
<tr>
<td>Planar Anisotropy ($\Delta r$)</td>
<td>inverse</td>
<td>direct</td>
<td>direct</td>
</tr>
<tr>
<td>Strength Coefficient ($K$)</td>
<td>non-linear</td>
<td>non-linear</td>
<td>direct</td>
</tr>
<tr>
<td>Strain Hardening Exponent ($n$)</td>
<td>direct</td>
<td>non-linear</td>
<td>non-linear</td>
</tr>
</tbody>
</table>

Table 1.1: Qualitative effect of process parameters on product quality

Note: direct = input/output relationship is directly proportional
       inverse = input/output relationship is inversely proportional
       non-linear = input/output relationship is non-linear

1.2 Problem Statement

Sheet metal forming is one of the most widely used manufacturing processes. Sheet metal is used in products such as aircraft, automobiles, furniture, and appliances. Despite its wide use, sheet metal forming is still more of an art than a science. The development of sheet metal forming processes is plagued with long lead times which result from many iterations of tryouts on expensive prototype tooling. Often, sheet metal dies must be modified during production to eliminate problems that arise.

The process of forming sheet metal is very complex and can only be understood through a considerable amount of training and experience. Sheet metal formability is affected by a large number of parameters such as material properties, blank configurations, die and press design and setup, and the complex interaction between the sheet, die, and lubrication. More powerful design tools are needed to help engineers design better products and processes and to reduce lead times and cost.
Therefore the goal of the proposed work is:

- To develop a part and process methodology for the deep drawing and stamping of sheet metal parts.
- To generate computerized educational tools to instruct engineers on the use of this proposed design methodology.

1.3 Dissertation Organization

Finally, the outline of this dissertation by chapters is:

1. Introduction and Problem Statement
2. Fundamentals of Deep Drawing and Stamping
3. Research Plan
4. Analytical and Numerical Modeling of Deep Drawing and Stamping
5. Experimental Investigation of Deep Drawing and Stamping
6. Part and Process Design Methodology for Deep Drawing and Stamping
7. Conclusions and Future Work
8. References
9. Appendices
CHAPTER II

FUNDAMENTALS OF DEEP DRAWING AND STAMPING

2.1 Deep Drawing - Process and Technology

In general, deep drawing (Figure 2.1) is a process whereby a blank or workpiece is forced into or through an open die by means of a punch to form a hollow component in which the thickness is essentially the same as the original material (Marciniak and Duncan, 1991). One major characteristic of deep drawing is that the mean normal stress is tensile. This limits the maximum possible strains that can be achieved before failure (Lange, 1985).

The major components of the cup geometry in classical (axisymmetric) deep drawing are shown in Figure 2.2. Initially, when the punch makes contact with the sheet, the material must bend around the punch and die radius. As the punch descends into the die, the perimeter of the blank moves towards the die cavity; this is the essence of deep drawing.

The majority of the deformation occurs in the flange of cup. The flange undergoes circumferential compression and radial tension. Once the material overcomes the compression of deep drawing though the flange, it must bend and unbend over the die radius. The force needed to cause deformation is not applied to the deformation zone. Instead, the punch applies the force to the bottom of the cup. This force is transmitted through the cup wall to the flange. Thus, fracture occurs in the cup wall just above the punch radius which is transmitting the largest forces and which is the least strain hardened. Typically, a blank holder is used to apply pressure on the outer perimeter of blank to decrease wrinkling and to increase the controllability of the process.
2.1.1 Drawability of Round Cups

The draw ratio \( (DR) \) of a deep drawing operation is calculated as the ratio of blank diameter \( (d_0) \) to cup diameter \( (d_1) \):

\[
DR = \frac{d_0}{d_1}
\]  

(Equation 2.1)
The limiting draw ratio (LDR) is the maximum draw ratio that can be obtained under perfect deep drawing conditions. LDR is considered a good measure of drawability of a material. To maximize the LDR (Lange, 1985):

- Decrease blank holder/sheet friction
- Increase punch/sheet friction
- Increase punch and die radius (this is limited by wrinkling)
- Increase strain hardening exponent (n-value in the equation $\bar{\sigma} = K[\varepsilon_0 + \bar{\varepsilon}]^n$)
- Increase normal anisotropy ($\bar{r}$-value)
- Decrease planar anisotropy ($\Delta r$-value)

For cup geometries with draw ratios greater than the LDR of a material, several drawing stages must occur. This is referred to as redrawing. Typically, the LDR for second and third drawing stages decreases significantly. To increase LDR for subsequent draw stages, annealing of the drawn cup can be employed. LDR's for various draw stages and different materials has been empirically determined as well as suitable lubricants. This information is listed in Table 2.1.

### 2.1.2 Effect of Strain Hardening

The strain hardening exponent $n$, in the equation $\bar{\sigma} = K[\varepsilon_0 + \bar{\varepsilon}]^n$, plays a very crucial role in sheet metal forming. Hosford and Caddell (1993) have shown that in a dimensionally inhomogeneous specimen, the n-value plays a significant role in maintaining strain uniformity. The relationship of n-value and drawability is ambiguous. A higher n-value strengthens the cup wall, but it also strengthens the flange so more force is needed to deform it. Nevertheless, the LDR increases with increasing n-value as shown by (Zunkler, 1973):

$$\ln(LDR) = \left(\frac{\eta_{\text{def}}}{1.1}\right)^{(n+1)} (n + 1)$$  \hspace{1cm} (Equation 2.2) (Zunkler, 1973)
Further, higher \( n \)-values improve deep drawing indirectly by increasing cup wall strength which allows higher blank holder forces to be used. Therefore, the \( n \)-value can be correlated to decreased wrinkling in deep drawing (Taylor, 1988).

<table>
<thead>
<tr>
<th>Material</th>
<th>First Draw</th>
<th>Second Draw without Anneal</th>
<th>Second Draw with Anneal</th>
<th>Lubrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Steel</td>
<td>1.8-2.0</td>
<td>1.2-1.3</td>
<td>1.6-1.7</td>
<td>Water/oil/soap emulsion</td>
</tr>
<tr>
<td>Stainless Steel:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferritic</td>
<td>1.55</td>
<td>2.0</td>
<td>1.25</td>
<td>Water-graphite paste or thick mixture of linseed oil and white lead oxide; sodium palmitate</td>
</tr>
<tr>
<td>Austinitic</td>
<td></td>
<td>1.2</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Heat Resistant Steel</td>
<td>1.7-2.0</td>
<td></td>
<td>1.6-1.8</td>
<td>Water-graphite paste or thick mixture of linseed oil and white lead oxide; sodium palmitate</td>
</tr>
<tr>
<td>Copper</td>
<td>2.1</td>
<td></td>
<td>1.9</td>
<td>Not available</td>
</tr>
<tr>
<td>Brass</td>
<td>1.9-2.2</td>
<td>1.3-1.4</td>
<td>1.8-2.0</td>
<td>Strong soap suds mixed with oil, soap, and grease containing oils emulsified in water, possible with amorphous graphite added; strong soap suds mixed with oil or rape oil</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.9-2.1</td>
<td>1.4-1.6</td>
<td>1.8-2.0</td>
<td>Kerosene with addition of amorphous graphite or rape oil, mineral grease, or brand name lubricants</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.9</td>
<td>-</td>
<td>1.7</td>
<td>Stearin or liquid palmin, PTFE films</td>
</tr>
</tbody>
</table>

Table 2.1: Limiting draw ratios and suitable lubricants for various materials (Lange, 1985)

2.1.3 Effect of Anisotropy

The \( r \)-value is a measure of plastic anisotropy in sheet materials and is defined as the instantaneous ratio of width strain to thickness strain during the plastic deformation of a tensile test.

\[
r = \frac{d\varepsilon_{\text{width}}}{d\varepsilon_{\text{thickness}}} \tag{2.3}
\]

An average or normal plastic anisotropy, \( \bar{r} \), is defined as:

\[
\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \tag{2.4}
\]
where \( r_{45} \) is the \( r \)-value at 45° from the rolling direction, etc (see Figure 2.3). The planar variation of the \( r \)-value is distinctly seen in a drawn cup. The top of the wall will form ears as shown in Figure 2.4. Essentially the material elongates and thins more along the ears. The planar plastic anisotropy, \( \Delta r \), is a measure of earing tendency and is defined as follows.

\[
\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2}
\]  \hspace{1cm} \text{(Equation 2.5)}

Increasing \( \bar{r} \)-value decreases the force to deform the flange while increasing the strength of the cup wall, as illustrated in Hill’s plane stress normally anisotropic quadratic yield function (see Figure 2.5):

\[
\bar{\sigma} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y \frac{2\bar{r}}{\bar{r} + 1}}
\]  \hspace{1cm} \text{(Equation 2.6)} \hspace{0.5cm} \text{(Hill, 1979)}

The flange is undergoing a tension/compression stress state which is represented by quadrant two of Figure 2.5. In quadrant two, increasing \( \bar{r} \) tends to decrease flow stress. Similarly, the cup wall is undergoing a tension/tension stress state which is quadrant one of Figure 2.5. Increasing \( \bar{r} \) tends to increase flow stress in this quadrant. Therefore increase \( \bar{r} \) tends to decrease the deformation force while increasing the load carrying capacity of the cup.

Under certain assumptions, Hosford (1993) derived an expression relating the limiting draw ratio to the \( \bar{r} \) value:

\[
\ln(LDR) = \eta \sqrt{\frac{\bar{r} + 1}{2}}
\]  \hspace{1cm} \text{(Equation 2.7)} \hspace{0.5cm} \text{(Hosford and Caddell 1993)}

In Equation 2.7, \( \eta \) represents an efficiency factor which varies with lubrication, blank holder force, material thickness, and die radius. Typical \( \eta \) values range from 0.74 to 0.79 (Hosford and Caddell, 1993).
Planar plastic anisotropy, $\Delta r$, has a minor but important effect on drawability. The higher the $\Delta r$ the more earing occurs. Earing typically must be trimmed, therefore, an increase in $\Delta r$ increases trimming and decreases the total depth of draw (Hosford and Caddell, 1993). It has been shown that the $r$-value has very little effect on the stretchability of a material (Blickwede, 1968).

Figure 2.3: The $r$-values in a sheet material (Crowley, 1998)

Figure 2.4: Earing in deep drawing (Hosford and Caddell, 1993)
Note: the arrow indicates rolling direction

Figure 2.5: Yield surface as a function of $\bar{r}$ -value (Hosford and Caddell, 1993)
2.1.4 Product Quality

Due to the circumferential compressive forces, buckling may occur in the sheet during deep drawing. Buckling in the flange is typically called wrinkling while buckling in the wall of a conical cup is called puckering. Wrinkling may be decreased or eliminated by (Lange, 1985):

- Increasing blank holder force
- Increasing material thickness
- Increasing normal anisotropy ($\bar{\kappa}$-value)
- Decreasing planar anisotropy ($\Delta\kappa$-value)

When the punch/die clearance is large the drawn cups are referred to as tapered walled cups. The difficulty in deep drawing tapered cups is that the wall is unsupported and undergoing circumferential compression. Even though the wall in a straight walled cup is also unsupported, at least wall wrinkling can be controlled by the tight punch/die clearance. Puckering may also be reduced by the above means for reducing wrinkling in straight walled cups or by the following additional means (Lange, 1985):

- Increasing the blank diameter
- Increasing blank holder/sheet friction
- Increasing drawbead restraint

In tapered cups, the only method to control puckering is to increase the radial tension in the wall. This may be achieved by increasing blank diameter, increasing blank holder force, increasing blank holder/sheet friction, and using drawbeads. There is a limit to the amount of taper that can be deep drawn. Once, this limit is exceeded, puckering will occur no matter how much blank holder force is applied.

2.1.5 Deep Drawing of Complex Geometries

A typical geometry is the rectangular pan as shown in Figure 2.6. In the drawing of rectangular shapes, the stresses are high in the corners due to the high deformation forces
required for the deep drawing condition that is occurring in this region. Thus rectangular pans typically fail in the corners. Stresses are usually low in the side regions of the pan. Upon springback, excess material is often trapped in the wall between the highly stressed corner regions causing distortions, side wall curl, and even oil canning. Figures 2.6 and 2.7 demonstrate the use of drawbeads to control metal flow in the deep drawing of rectangular pans. Drawbeads increase the restraining force applied to the sheet by making the sheet bend and unbend as it flows through the binder surfaces.

Non-round parts can be analyzed with round cup equations by using an equivalent blank and punch diameter which are calculated based on equating the areas of the rectangular blank and punch to an equivalent round blank and punch. Since high r-values increase round cup deep drawing it is desirable to orient the high r-value directions (0° and 90° from rolling direction) of the blank along the corners of the pan. Rectangular blanks that are cut at 45° from the rolling direction orient the high r-value directions along the corners of the rectangular pan and thus improve the depth of draw (Hobbs, 1974). Thus, in the case of non-round parts, the high r-value directions of the blank should be placed along the regions which experience deep draw conditions.
2.2 Stamping - Process and Technology

The process of stamping is characterized by the use of matched die and punch surfaces rather than an open die cavity as shown in Figure 2.8. Since, stamping is characterized by bending, stretching, and deep drawing deformation modes, a net thinning is observed in the final product. In general, stamping exhibits more stretching than deep drawing. Stamping provides more control over the material and is therefore capable of forming more complex geometries with reentrant and concave shapes when compared to deep drawing.

Figure 2.8: Schematic of a stamping process (Diller, 1997)
2.2.1 Product Quality

The forming of reentrant shapes in stamping is referred to as embossing. Embossing includes the forming of such automotive features as door handle cavities, license plate cavities, or door window cavities. Geometric distortions are also associated with embossing. During an embossing operation the material around the cavity is supported only on one side by the male die half. Once the embossing tool makes contact with the sheet, compressive forces due to the material deformation cause the sheet to buckle.

Before an embossing operation, the strain distribution in a stretch-drawn panel is fairly uniform. During the embossing operation, the strain distribution becomes non-uniform due to the variation in material deformation around the cavity. This non-uniform strain pattern increases the residual stresses and promotes the so called “rabbit earing” effect upon springback. One method proposed to reduce rabbit earing consists of using a pressure pad in the female die cavity. This pad would suppress the buckling of the material during the embossing process and provide better control over the metal deformation as shown in Figure 2.9.

By increasing the amount of stretch, springback is reduced because the variation in strain through the material thickness caused by localized bending is minimized. Increased stretch increases the level of strain hardening thereby increasing strength, hardness, and dent resistance. Figures 2.10 and 2.11 demonstrate that increasing strain decreases springback and increases dent resistance. These effects are saturated at about 2% strain, therefore 2% is a good target for minimum strain in a stamping.

2.2.2 Effect of Material Properties

In a tensile test of a Holloman material ($\sigma=Ke^n$), the n-value is numerically equivalent to the uniform true strain. Therefore, the larger the n-value the more elongation can occur before necking (Wick, 1984). Hecker (1974) has shown that limiting depths of hemispherical dome tests can be related to n-value. Hosford and Caddell (1993) have
shown that increasing n-value tends to improve the strain distribution in a dimensionally inhomogeneous material.

It has been shown that the r-value has very little effect on the stretchability of a material. This is due to the fact that increasing r-value tends to increase the flow stress in biaxial tension. Thus for stretching, increasing r-value increases the deformation loads and increases the load carrying capacity of the material. Blickwede investigated the effect of n and \( \tilde{r} \) on the forming of various automobile panels (Blickwede, 1968). The quality of a door panel, which was primarily a stretching operation, is highly dependent on n and hardly dependent on \( \tilde{r} \). The quality of a blower housing, which was primarily a deep drawing operation, is highly dependent on \( \tilde{r} \) and hardly dependent on n. The quality of a dashboard panel, which involved both stretching and deep drawing, was dependent on both n and \( \tilde{r} \).

![Diagram of stretch-draw process]

Figure 2.9: Stretch-draw process with pad action (Crowley, 1998)
2.2.3 Automotive BodyStamping

Typical outer panels are illustrated in Figure 2.12 (Diller, 1997). Because most outer panels are only very lightly contoured, they require a stretching or stretch-drawing operation. The surface quality of the panel must meet a rigorous inspection using high gloss paints and reflections from fluorescent lighting.

Dent resistance is another important feature in outer panels. Panels are tested to ensure that slight denting resulting from palms and elbows leaning against panels or from minor collisions will immediately spring back without adding permanent deformation to the panel. Thus the adherence to the 2% minimum strain rule is highly recommended.

Most inner panels contain deep recesses which increase stiffness. Unlike outer panels, these parts can not usually be fully stretched, thus stretch-drawing or deep drawing is required in the process design. A typical automotive stamping process sequences includes several key steps as shown in Figure 2.13. These steps typically include:

1. Blanking
2. Binder Wrap and Clamping
3. Stamping
4. Trimming and Piercing
5. Flanging and Hemming
Figure 2.12: Outer automotive body panels (Diller, 1997)

Figure 2.13: Various press and die configurations (Shulkin, 1998)
The blanking process is used to cut the initial blank shape from the coil of metal. The binder wrap stage is a simple positioning of the sheet on the face of the binder and allowing it to conform to the binder surface geometry due only to gravity. Although the binder surface may be flat, typically the binder is contoured to provide ample material in the die cavity during forming.

The binder surfaces come together to clamp the sheet along its edges and a binder pressure is applied to create frictional restraining forces which help to control material flow during forming. The binders also serve to set the drawbeads which add to the restraining forces through bending and additional friction. During the forming stage, the matched punch and die surface come together and impart large plastic deformations to the sheet in order to form the part geometry. For more complex panels, more than one forming stage is often necessary to avoid fracture.

The tooling design of automotive stampings is typically divided into two stages (Burk, 1996). The first step is draw design which includes determination of the tooling surfaces and orientations which are necessary to achieve a successful draw. This involves the design of the punch, die, binder, addendum, and other features which will define the material flow during forming. The next step is die design which deals with press and structural related issues. The goal of this stage is to create functional tooling which is as stiff and light as possible. The steps in tool design are typically:

1. Process Sequence Design
2. Tip Angle Determination
3. Binder Development
4. Punch Opening Layout
5. Addendum Design
6. Drawbead Layout
One consideration of binder design is whether the press is a single or double action and whether a three or four piece die is required as shown in Figure 2.13. The curvature of the binder affects the amount of material available within the die cavity during forming, therefore, binder design is very important in inducing the appropriate amount of stretch in the panel. The binder surface must be a developable surface which means that the sheet should be able to conform to the binder without wrinkling or stretching.

The region between the part geometry and binder surface is called the addendum. The addendum is often used to alter the material flow, to increase stretching in the part, and to simplify subsequent operations as flanging (Burk, 1996). Drawbeads are often added to the binder surface to further restrain material flow and cause further stretching in the panel without increasing the amount of clamping force necessary to hold the blank. Various mathematical models and design guidelines are available for designing drawbeads which provide an appropriate amount of restraining force (Tufekci, 1994).

2.3 Blank Holder Force

The blank holder's main function is to apply a blank holder pressure (BHP) onto the flange to suppress wrinkling that may be caused the compressive stresses that occur there. If a blank holder is not used or insufficient blank holder force (BHF) is applied, then the cup may wrinkle as shown in Figures 2.14a and b.

The secondary function of the blank holder is to control and restrain the material flow into the die by increasing the friction forces in the flange and radial tension in the part. The increased radial tension must be supported by the part wall, thus if too much BHF is applied then fracture may result before the desired draw depth is attained as shown in Figure 2.15a.

With a correctly applied BHF, a good part can be obtained as shown in Figure 2.15b. Draw depth is therefore limited by the onset of wrinkling and fracture which can be
visualized on a drawability chart which is shown in Figure 2.16. The fracture and wrinkling limits are plotted as lines in BHF/draw depth space and these lines intersect at the maximum possible draw depth.

Figure 2.14: Wrinkling in experimental and simulated round cups (ERC/NSM labs)

Figure 2.15: Fracture in experimental round cups (ERC/NSM labs)
2.3.1 Issues with Blank Holders

Problems may arise if the blank holder contacts the blank at high speeds. High speed contact may cause large spikes in the load/stroke curve as shown in Figure 2.17. This may lead to excessive noise, increased press and die wear, and loss of lubrication on the blank. These problems may be eliminated by reducing the relative speed of the ram just before the blank holder contacts the blank using advanced technologies (Ahmetoglu, 1996).

Variances in blank holder force that occur during production may be caused by wear in the die or press, misalignment of the tooling, and changes in material thickness. According to Karima and Donatelli, a .004” change in material thickness can increase the blank holder forces by 15% in a mechanical press if the shut height is not adjusted (Karima and Donatelli, 1989). Unless the drawability window is sufficiently large, the blank holder force should be monitored to ensure product quality. Further, the blank holder plate should be inspected regularly for surface degradation due to wear from metal flow contact.
2.3.2 Blank Holder Design

One issue with blanks holders is how to implement drawbeads into them. There are several strategies that can be employed in the design of blank holders with drawbeads. Figure 2.18a shows how drawbeads and a stopblock can be employed to control the material flow. Figure 2.18b shows how drawbeads and blank holder pressure can be used together to control the deformation process. In the first case, the BHF is unknown unless a load monitor is installed in the tooling. The effective BHF is essentially the force required to maintain contact with the stopblock. Clearly, this method relinquishes some of the control that is provided when drawbeads and BHP are used together and also eliminates the possibility of varying the BHP during the process (see Section 2.3.3).

In the second case, BHP is applied to the sheet and a drawbead is used. The best method which ensures maximum control is to apply the BHF only on the inside of the bead.
Applying the BHF to the outside of the bead tends to reduce control, because the area of contact is changing throughout the process and may go to zero if the sheet draws completely through the drawbead. By applying the BHF to the inside of the bead only, control over the process is relinquished only when the sheet draws completely into the die cavity. Further, this method takes advantage of time and location variable BHF as will be discussed in Section 2.3.3.

For more complex stampings, it often becomes necessary to use blank holders with non-flat surfaces. By utilizing a curved binder surface, more material can be forced into the die cavity before the deformation process even begins as shown in Figure 2.12. Depending on the geometry of the stamping, various binder surface geometries may be employed such as the ones shown in Figure 2.19.

The main criterion for binder surface design is its developability. A developable surface is a topological concept which requires that the flat sheet can attain the developable surface shape without stretching or wrinkling. Developable surfaces include planar, cylindrical, conical, and combinations of these. Non-developable surfaces are acceptable only when there is minimal straining or buckling of the sheet.

Typically, the press and tooling are assumed to be rigid and parallel in computer simulations, even though it is well know that this is not the case. Elastic deflections and non-parallelism in the tooling and press can cause problems in conventional stamping operations such as non-uniform BHP or even loss of contact. Elastic deflections and non-parallelism may be caused by a variety of reasons including cushion pins of unequal length, and worn out and poorly manufactured tools and presses. Even stiffening ribs in tools can cause variation in the BHP due to the sudden local changes in tool stiffness.
Figure 2.18: Using drawbeads and blank holder simultaneously

Figure 2.19: Types of binder surfaces (Doege, 1995)
One method to reduce the effect of elastic deflections and non-parallelism is to use manifolde nitrogen or hydraulic cylinders to impart the BHF. The manifolding of cylinders ensures that each cylinder transmits an equal force and thus the effects of elastic deflections and non-parallelism are reduced. The pressure pattern caused by elastic deflections can be measured with pressure sensitive paper or predicted using computer simulations as shown in Figure 2.20.

When using nitrogen or hydraulic cylinders, it is desirable to maintain as uniform a BHP pattern as possible. One method is to design a very stiff or rigid blank holder that would ensure a uniform BHP. The problem with this is that any non-parallelism would have an even greater effect on the process. Also, a rigid blank holder eliminates any possibility of applying a non-uniform BHP onto the sheet which could be desirable (see Section 2.3.3).

Another method is to design a blank holder which is made up of very rigid segmented sections as shown in Figure 2.21. This method provides good independent control over the material, but the tool design is complex and the segments may damage the sheet surface. Another strategy is to design a one-piece binder which is made up of rigid cones which are elastically connected as shown in Figure 2.22 (Siegert, 1998). Although this design is complex, it can be readily sand casted and it provides good control and a non-damaging contact on the sheet.

Alternatively, the blank holder can be designed as one-piece and elastic. The contact of a cylinder piston and an elastic blank holder causes a pressure pattern at the blank holder/sheet interface as shown in Figure 2.23. This pressure pattern is high at the center of contact and decays exponentially radially outward. The effective range ($r_e$) can be defined as the radius at which 90% of the BHF of the cylinder is inside.

If the effective range is too small then there will be regions of low BHP where the sheet will not be properly controlled. If the effective range is too large, then the actions of the
cylinders will be coupled which will cause a loss of independent control of the cylinders. Shulkin (1998) studied this problem and determined that for a given cylinder and blank holder, a proper effective range could ensured by calculating an appropriate blank holder thickness.

Shulkin (1998) developed equations which determines the pressure pattern which is developed in the simplified cylinder/blank holder model in Figure 2.23.

$$\sigma_{zz}(r,z) = \int_0^\infty \frac{\xi F(\xi)}{d(\beta)} \left\{ \frac{\xi S^2 + (\beta + SC)}{S_z} + \left[ S^2 - \beta^2 + \xi z (\beta + SC) \right] C_z + \right.$$  

$$+ \frac{h^4}{6\beta^4} \left[ (\xi SC + S^2) S_z + (SC + \beta + \xi z S^2) C_z \right] \right\} j_0(\xi r) d\xi$$  

(Equation 2.8)

Where $d(\beta)$, S, C, $S_z$, $C_z$, $\beta$, $F(\xi)$ and l are given in Appendix A.3. Shulkin (1998) implemented these equations into a computer program to be used as a tool for proper elastic blank holder design. Also, the degree of coupling or dependency of the cylinders can be determined with this program. For example if the effective range was designated as $r_e$ and the distance between cylinders one and two was $x_{12}$, then a coupling factor, $f_c$, can be defined as follows (see Figure 2.24):

$$f_c = \frac{2r_e - x_{12}}{x_{12}}$$  

(Equation 2.9)

Thus for $f_c \leq 0$, the cylinders are uncoupled. For $0 < f_c < 1$, the cylinders are partially coupled. For $f_c \geq 1$, the cylinders are fully coupled as shown in Figure 2.24.
a) Experimentally measured with pressure sensitive paper (Shulkin, 1997)

b) Predicted with computer simulations

Figure 2.20: BHP distribution for a 25.4 mm (1") thick blank holder

Figure 2.21: Segmented blank holder (Siegert, 1995)

Figure 2.22: One piece blank holder optimized for BHF control (Siegert, 1998)
Figure 2.23: Pressure pattern caused by deep drawing with a nitrogen or hydraulic cylinder (Shulkin, 1998)

Figure 2.24: Coupling factor
2.3.3 Blank Holder Force Control

Two problems arise in the conventional application of blank holder force. First, a constant blank holder force is typically applied throughout the forming stroke even though the draw ratio decreases as the flange is drawn in as shown in Figure 2.25. Second, a uniform blank holder force pattern (around the binder periphery) is typically applied to the blank even though this may not be the optimum pattern. Compressive forces in the flange not only restrain material flow, but cause the material to thicken. The thickened areas are subject to high blank holder pressure (BHP) concentrations during the deep drawing process which further restrains material flow as shown in Figure 2.26.

Also, a uniform BHP may be optimal for round cup deep drawing of planar isotropic materials, but for more complex geometries and materials, a non-uniform BHF may be more optimal. To improve the effect of blank holder force, individually controlled nitrogen or hydraulic cylinders are used to apply the blank holder force as shown in Figures 2.27 and 2.28. Material flow can be locally controlled with this method throughout the stroke of the press.

![Diagram](image_url)

Figure 2.25: Reduction of draw ratio during the deep drawing process
Figure 2.26: Predicted pressure concentrations on a rectangular pan due to material thickening

Figure 2.27: Blank holder force control using hydraulic cylinders in a rectangular pan tooling (ERC/NSM equipment)

Figure 2.28: Four point blank holder force control system (Siegert, 1991)
Time variable BHF does occur in industrial stamping processes, but typically not in an optimal fashion. In double action mechanical presses, BHF is applied with a position setting of the outer ram. Typically the BHF is not even known unless a loadcell is installed. The BHF tends to vary with the action of the mechanical linkage. In air or nitrogen cushions, the BHF typically increases slightly with ram stroke due to the compression of the gas. In a hydraulic cushion, the BHF is typically constant throughout the ram stroke. Each of these BHF profiles are not optimal because they do not vary in time in the optimal manner.

Location variable BHF is applied in industry by experienced tryout personnel who grind the die surface or shim the tooling sections or cushion pins. Using a system, such as the one built by the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) and shown in Figure 2.27, can clearly improve the application of BHF when compared to grinding and shimming.

There have been many proposals and investigations on how to vary the BHF as a function of press stroke and position around the binder. A reasonable time varying BHF control strategy which has been shown to improve on constant BHF is to vary the BHF from the fracture limit to wrinkling limit of the BHF as shown in Figure 2.29b (Kuri, 1995). Another empirical method for location variable BHF which improves on the uniform BHF is to distribute the BHF in proportion to the length to width ratio of the die cavity as shown in Figure 2.30b (Doege, 1995).

Another strategy for time varying BHF control is to pulsate the blank holder force. Two pulsating BHF strategies are shown in Figure 2.31. This first pulsating strategy is to vary the BHF sinusoidally within the fracture and wrinkling limits. The purpose of this strategy is to reduce the frictional conditions at the binder/sheet interface (Siegert, 1997). The second pulsating strategy is to allow the sinusoidal BHF to dip below the wrinkling limit level. This allows the flange of the part to wrinkle slightly during the process.
allowing the material to draw much more freely into the die cavity. The wrinkles are flattened out by the high points of the BHF pulsations. This method can greatly increase the drawability, but care must be taken to not dip below the wrinkling limit too much, or the wrinkles will fold over instead of flattening.

By controlling the blank holder force as a function of press stroke and position around the binder periphery, one can improve the strain distribution of the panel providing increased panel strength and stiffness, reduced springback and residual stresses, increased product quality and process robustness. An inexpensive, but industrial quality system is currently being developed at the ERC/NSM using a combination of hydraulics and nitrogen and is shown in Figure 2.32 (Shulkin, 1996). Using BHF control can also allow engineers to design more aggressive panels to take advantage of the increased formability window provided by BHF control.

Figure 2.29: Time variable BHF control strategies

<table>
<thead>
<tr>
<th>BHF</th>
<th>STROKE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FRACTURE LIMIT</td>
</tr>
<tr>
<td></td>
<td>WRINKLING LIMIT</td>
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</tbody>
</table>

a) Constant BHF

b) Ramp BHF - fracture to wrinkling
Figure 2.30: Location variable BHF control strategies (Doege, 1995)

Figure 2.31: Pulsating BHF control strategies
Passive Hydraulic Action
Nitrogen Return
Four Cylinders
80 ton capacity
5” Stroke Max
Two Channels of Control
Closed or Open Loop

Figure 2.32: Passive blank holder force control system (ERC/NSM equipment, Shulkin, 1996)

2.3.4 Closed-Loop BHF Control
An optimum time and location variable blank holder force may be obtained experimentally, or iteratively using FEM simulations, but this is a time consuming process. Optimal BHF profiles may be predicted analytically, but so far analytical models have not correlated very well with empirical observations.

2.3.4.1 Round Cups - Experimental Optimal BHF Profiles
Kergen (1992) equipped a closed-loop control system to control the BHF in a round cup deep drawing process. The advantage of closed-loop control of the BHF is that the difficulty of determining the optimum BHF profile is removed. Furthermore, variations caused by material, lubrication, die wear, heat and other process disturbances can be absorbed by the closed-loop system, thereby making the process more robust to process variations. Kergen’s BHF control system measures the distance between binder surfaces (wrinkling limit control strategy) and punch force (fracture limit control strategy) and uses them as feedback signals to regulate the BHF (Jirathearanat, 1998).
The wrinkling limit control strategy consists of monitoring the distance between the binder surfaces (or the binder gap) in order to detect wrinkling. The system compares the current binder gap with a predicted current sheet thickness (this varies with the amount of draw-in of the material). If the measured value is above the predicted one the BHF is increased; below this value the BHF is decreased. A proportional, integral, derivative (PID) controller is used to determine how much the BHF is changed in order to maintain the specified binder gap. Figure 2.33 shows the measured BHF using this control strategy. The advantage in this approach is that the obtained BHF profiles are actually the minimum necessary BHF to suppress wrinkling. The application of this profiled BHF offers less severe forming conditions to form less formable materials.

The fracture limit control strategy consists of using a closed-loop control system to obtain BHF profiles that maintain a predetermined punch force. In this system, the punch force is kept just below the punch force which would cause fracture in the material (determined through constant BHF experiments, see Figure 2.34). By utilizing this method, the BHF is maintained at a level which maximizes the strain in the sheet without fracture. Thus this method tends to increase dent resistance and stiffness and decreases springback. Further, limiting draw ratios are dramatically increased, due to the increased stretching of the material that is obtained.

Manabe (1995) developed a round cup deep draw tool with closed-loop fuzzy controlled blank holder force. The control algorithm was designed to achieve a uniform wall thickness through the use of two evaluation functions. The first function evaluated the deviation of the punch versus blank reduction ratio curve from an experimental punch curve going near the fracture limit. The second function evaluated the deviation of the maximum flange thickness from the initial blank thickness (which determined the wrinkling limit). The resulting BHF profile is shown in Figure 2.35. With this control strategy, more uniform thickness distribution was achieved, thinning at the flange nose was reduced, and thickening of the flange was suppressed which, in turn, prevented the
blank holder lift-up and the flange wrinkling. Later, a learning algorithm was added to the controller (Yoshihara, 1996), which resulted in an even more uniform thickness distribution throughout the cup wall (Shulkin, 1998).

This is an extremely sophisticated method and is quite powerful, but the extensive experimentation that is required is impractical for industrial use. Furthermore, a control strategy based on the simultaneous use of both wrinkling and fracture criteria does not add anything to the process, because a fracture limit control strategy is enough to avoid wrinkling. If the part wrinkles under a fracture limit BHF, then the part is more than likely impossible to form. The failure of this process is embedded in the geometry of the part and tooling and not in the process. The same reasoning works for a wrinkling limit control strategy.

Figure 2.33: Measured BHF profile with closed-loop control based on wrinkling limit strategy – round cup deep drawing (Kergen, 1992)

Figure 2.34: Measured BHF profile with closed-loop control based on fracture limit strategy – round cup deep drawing (Kergen, 1992)
2.3.4.2 Round Cups - Computer Simulation of Optimal BHF Profiles

Traversin (1996) integrated closed-loop control into FEM simulations for round cup deep drawing to determine the optimum time profiled BHF in a round cup deep drawing process. Optris and Ficture, commercially available FEM codes, were used in these investigations. Similar to the closed-loop control system of Kergen (1992), the binder gap and punch force were used as feedbacks of the control system. The reference inputs were the thickness evolution of the blank and a specified punch force equivalent to 80% of the maximum punch force found during constant BHF simulations which led to material fracture.

For the wrinkling base control, the current binder gap was compared to the current maximum thickness of the material and the BHF was controlled accordingly to avoid wrinkling. For the fracture based control, the current punch force was compared to the specified punch force and the BHF was controlled to maintain a specified punch force. A proportional, integral, derivative (PID) controller strategy was implemented into the FEM
code to determine the amount the BHF needed to be changed in order to maintain the
specified punch force or binder gap.

The simulation results of Traversin’s work show good agreement with the experimental
results of Kergen. Kergen and Traversin explain the discrepancies as the results of
inappropriate friction conditions, improper reference inputs (i.e. thickness evolution), and
coarse time intervals. The problem with the work of Kergen and Traversin is that
wrinkling based strategy does not attempt to maximize the part strain in order to improve
final product properties such as dent resistance, stiffness, and springback. Also, the
fracture based strategy relies on a specified punch force which was developed from
extensive constant BHF experiments. Also, punch force is not the best indicator of
fracture. Further, their work did not provide detailed information on control strategies for
location and time variable BHF.

Cao and Boyce (1994) implemented a closed-loop control strategy into the commercial
FEM code Abaqus for round cup deep drawing. A theoretical wrinkling based criterion
and the maximum major strain were used simultaneously as feedbacks to regulate the
BHF in round cup deep drawing. The predicted BHF profile (Figure 2.36) shows a
gradual increase of BHF with the punch displacement. The problem with Cao and
Boyce’s method is that the maximum strain is not the best indicator of fracture. The
maximum strain at fracture is a function of both major and minor strain. Only monitoring
the major strain will lead to under- or overestimation of the failure limit. Furthermore,
their method controls the BHF using the wrinkling limit method at the beginning of the
process and the fracture limit method at the end. It could be possible in a complex
stamping, that fracture was more likely at the beginning than wrinkling and wrinkling
was more likely at the end, therefore Cao and Boyce’s control strategy would fail in this
case. Clearly, their strategy was formulated for simple round cups only. Finally, the use
of two feedbacks was unnecessary as previous explained.
Osakada (1995) studied deep drawing of round cups in a tooling with the BHF controlled by an air compressor and an open-loop control valve. The optimum BHF trajectory was developed by a controlled FEM simulation in which a manual feedback algorithm maintained the BHF above the wrinkling and/or flange thickening limits but below the localized thinning limit. The resulting BHF trajectory (Figure 2.35) was applied and the following advantages were observed: the LDR was increased from 1.88 to 1.98, thinning was reduced as compared with a constant high BHF, and wrinkling was reduced as compared with a constant low BHF (Shulkin, 1998). The problem with this strategy is that controlled FEM is laborious and not practical. It can be used to prove a control strategy, but is impractical otherwise. Thinning is not the best choice for a fracture criterion, because the maximum value of thinning varies with biaxial strain.

![Graph showing BHF profile](image)

**Figure 2.36:** Predicted BHF profile obtained from closed-loop controlled simulation based on wrinkling and critical strain (Cao and Boyce, 1994)

2.3.4.3 Round Cups - Analytical Prediction of Optimal BHF Profiles

Kawai (1961) derived a semi-empirical equation for critical BHP (current BHF over initial area of blank in contact) for round cups based on the allowable specific wave amplitude of wrinkles. The predicted BHF profile is shown in Figure 2.35. Both Kawai and Thiruvarudchelvan (1990) experimentally verified this theoretical work using open-
loop BHF control. It was reported that the application of Kawai’s method minimized frictional resistance on the blank, eliminated flange wrinkling, reduced the punch force, reduced thinning at the punch nose area, and increased the LDR by 5% when compared with constant BHF (Shulkin, 1998). The problem with this work is that it is based on wrinkling and does not attempt to maximize strain.

Manabe (1987) derived equations to calculate fracture limit BHF trajectories for round cup deep drawing. However, the experimentally determined BHF curves differed considerably from the ones predicted by the equations. Nevertheless, Manabe observed dramatic improvement of the drawability using experimentally determined, fracture limit based, closed-loop control BHF profiles as shown in Figure 2.35 (Shulkin, 1998). The weakness in this investigation is that Manabe does not take into account anisotropy or wrap angle in his derivations.

Ahmetoglu (1996) used finite difference method (FDM) analysis to develop an optimum BHF variation for round cup deep drawing on a single action hydraulic press with an open-loop controlled die cushion. The analysis was based on three criteria: 1) maintaining the punch force below a calculated failure value, 2) maintaining the radial sheet tension below a calculated failure value, and 3) maintaining the cup wall thickness above a user specified value. The application of the BHF profile obtained with the above procedure (Figure 2.35) resulted in an increase of the LDR (Shulkin, 1998). The weakness of this work is that three control criteria are required, making the control strategy redundant and difficult to implement.

2.3.4.4 Non-Round Parts- Experimental Optimal BHF Profiles

Siegert (1996) designed a closed-loop, BHF control system for round cup and rectangular pan deep draw tools. He used punch force, binder gap, friction force, and draw-in as feedbacks to the control system. A piezoelectric sensor in the binder measured the friction force during the process and was used as a feedback loop as shown in Figure
2.37. Spring loaded pin sensors were installed on the tooling to measure the position of the blank edge during the process and was also used as a feedback loop. Siegert reported good improvement of drawability using this control strategy and an increase in process robustness.

For the rectangular pan case, Siegert (1998) implemented a system of ten individually controlled hydraulic cylinders to control the BHF as shown in Figure 2.22. Siegert suggested that one strategy for spatial control of BHF is to provide as uniform a BHP pattern as possible. Siegert has also developed a method to control the pressure in a nitrogen cylinder as a function of stroke thereby making the BHF control process much cleaner (Schlegel, 1994). The problem with Siegert’s work is that the reference curves for the friction force and draw-in were determined from laborious constant BHF experiments. This technique may limit the amount of improvement that may be attained using BHF control to the level of constant BHF.

Doege (1995) extended the fracture limit closed-loop control method to experimental non-symmetric parts. The die cavity consisted of four sides of different lengths. Parts were drawn using a deep drawing tool with four point BHF control, one BHF control cylinder on each side of the part. The initial values of the BHF were determined by a trial-and-error procedure. The force of each cylinder was adjusted proportionally to the corresponding side length (Figure 2.35). This control method resulted in a uniform distribution of the BHP around the flange. Cracks and wrinkles, observed for a constant BHF, were eliminated (Shulkin, 1998). The problem with this work is that it relied on laborious experimentation to determine the initial values of the BHF which would be impractical for industrial use.

Hardt (1993) developed a closed-loop BHF control algorithm to draw laboratory conical cups and square parts with dissimilar corner radii. The control strategy was to make the BHF converge to an optimum constant BHF from any initial BHF level as shown in
Figure 2.35. The two control variables were the tangential force at the punch nose and the normalized average thickness which were determined from experiments with constant BHF. Experiments demonstrated that for variable friction conditions and different blank diameters, the BHF trajectories converged to the optimum constant BHF from any starting BHF level. By using this method, the maximum possible cup depth could be consistently achieved from any starting BHF level thus making the process more robust (Shulkin, 1998). The problem with this strategy is that the reference inputs are based on extensive experimentation using constant BHF. This might limit the improvement that can be obtained using BHF control.

Kergen (1992) has also implemented a closed-loop BHF control system into a rectangular pan deep drawing tooling. This system consisted of eight cylinders and four independent channels of control. Kergen suggested to distribute the BHF so as to ensure a uniform BHP pattern, but does not suggest a method to predict an optimal spatial pattern of the BHF.

Figure 2.37: Measured BHF profile with closed-loop BHF system and friction force feedback (Lubricants: ZEPH \(\mu=0.13\), ZE \(\mu=0.11\), KTL \(\mu=0.075\)) (Siegert, 1996)
2.3.4.5 Non-Round Parts- Computer Simulation of Optimal BHF Profiles

The author of this dissertation has conducted experiments and simulations of a deep drawn rectangular pan in which eight nitrogen cylinders were used to impart the BHF (Thomas, 1997). Two control groups were used to apply a location variable BHF pattern, thus the simulation needed to model the elasticity of the blank holder as shown in Figure 2.38. Location variable BHF was shown to improve the fracture depth of rectangular pans up to 25%.

Shulkin (1998) conducted simulations of a viscous pressure formed (VPF) non-symmetric four sided panel in which the BHF was controlled using eight independently controlled hydraulic cylinders as shown in Figure 2.39. The elasticity of the blank holder as well as the contact of the cylinders were taken into account. The results of the simulations were used by the Extrudehone Corporation to design the laboratory setup and develop the process of VPF forming of the non-symmetric panel for experimental purposes. The weakness of both of these investigations was that a systematic method to predict optimal spatial patterns of BHF was not developed.

![Figure 2.38: Simulation of a rectangular pan deep drawing with an elastic blank holder (Thomas, 1997)](image1)

![Figure 2.39: Simulation of a VPF formed non-symmetric panel with an elastic blank holder (Shulkin, 1998)](image2)
2.4 Analysis Techniques

2.4.1 Mathematical Modeling

2.4.1.1 Round Cup Deep Drawing

In round cup deep drawing, the cup height (h) that is obtained from a particular blank diameter \(d_0\), cup diameter \(d_1\), and flange length \(f\) is calculated by assuming constancy of volume and no thickness change as shown below (Lange, 1985). Please refer to Figure 2.40 for a description of the symbols used for round cups.

\[
h = \frac{d_0^2 - (d_1 + 2f)^2}{4d_1} \quad \text{(Equation 2.10)}
\]

Using the same assumptions, simple formulas to calculate an initial geometry of the blank can be determined. For example, the diameter of a blank for a round cup with vertical walls and a flange is given as:

\[
d_0 = \sqrt{(d_1 + 2f)^2 + 4d_1h} \quad \text{(Equation 2.11)}
\]

The drawing force \(F_d\) can be calculated using the following equation derived by Siebel (1955). A complete development of this equation is shown in Appendix A.1.

\[
F_d = (\pi d_0 t_0) \left[ (e^{0.5\mu\pi}) \left( 1.1\sigma f \right) \ln \left( \frac{d_1}{d_w} \right) + \left( \frac{2\mu F_b}{\pi d_0 t_0} \right) + \left( \frac{\sigma d f_0}{2 r_d} \right) \right] \quad \text{(Equation 2.12)}
\]

(Siebel, 1955)

The first term in the large brackets of Equation 2.12 captures the force to overcome friction at the die radius. The second term calculates the force to overcome the compressive forces in the flange. The third term takes into account the friction at the blank holder/sheet interface. The final term calculates the bending forces at the die radius. Equation 2.12 does not take into account the anisotropy of the sheet or the evolution of the wrap angle around the die radius.
Equation 2.12 calculates the drawing forces at any stage of the process. The term $d_f$ refers to the instantaneous flange diameter at the desired stage of deep drawing and can be calculated by assuming contancty of volume and no thickness change.

$$d_f = \sqrt{d_0^2 - 4d_i h} \quad \text{(Equation 2.13)}$$

In order to use Equation 2.12, the average flow stress in the flange ($\sigma_f$) and die radius ($\sigma_d$) must be calculated. This is done by calculating the strain at points 1, 2, and 3 as shown in Figure 2.41 and using the flow stress equation $\bar{\sigma} = K[\varepsilon_0 + \bar{\varepsilon}]^n$ to calculate the stresses at these points. The average flange flow stress is calculated by averaging stresses 1 and 2 and the average flow stress over the die radius is the average of stresses 2 and 3. Please refer to Appendix A.1 for the equations to calculate the strains and stresses at points 1, 2 and 3.

Due to the compressive stresses that develop in the flange, a blank holder is used to apply pressure to suppress the wrinkling. Siebel has suggested the following empirical equation to calculate the blank holder pressure ($p_b$) necessary to suppress wrinkling. The factor $c$ ranges from 2 to 3. The term DR is the draw ratio.

$$p_b = 10^{-3} c \left[ (DR - 1)^3 + \frac{0.005d_w}{t_0} \right] S_u \quad \text{(Equation 2.14)} \quad \text{(Siebel, 1955)}$$

The drawing load must not exceed an amount greater than the fracture load ($F_{fr}$). Since fracture tends to occur at the cup wall near the punch radius, the fracture load is calculated by determining the force which causes the stress in the fracture region to reach the ultimate stress of the material (uniaxial conditions, anisotropy and thinning not included).

$$F_{fr} = \pi d_w t_0 S_u \quad \text{(Equation 2.15)} \quad \text{(Siebel, 1955)}$$

Under certain assumptions, Siebel calculated the limiting draw ratio as follows:
\[ LDR = \exp \left( 0.75 \times \frac{S_n}{1.1 \sigma_f} + 0.25 \right) \]  

(Equation 2.16) (Siebel, 1955)

Where \( \sigma_f \) is defined by Equation A.7 at full draw depth.

![Figure 2.40: Symbols used for round cup analysis](image)

![Figure 2.41: Stress calculation locations](image)

2.4.1.2 Deep Drawing of Rectangular Pans

To analyze rectangular pans using round cup deep drawing equations, one may calculate an equivalent blank diameter by equating the areas of the rectangular blank and equivalent round blank with the following equation. Please refer to Figure 2.42 for a description of the symbols used for rectangular pans.

\[ d'_0 = \sqrt{\frac{4l_0 w_0}{\pi}} \]  

(Equation 2.17)
A similar procedure may be used to calculate an equivalent punch and die diameter for the rectangular tooling (Lange, 1985).

To design a blank for a rectangular panel with vertical walls and a flange, a more involved procedure must be used. The width \( w_0 \) and length \( l_0 \) of the blank are calculated by unfolding the length and width sections of the panel. The corner radius \( r_0 \) of the blank is calculated by assuming the corner of the panel is a round cup. The dimensions of the blank are then adjusted using empirical based formulas to take into account the actual deformation patterns of rectangular panels.

This procedure and the equations were outlined by Lange (1985), but the author of this dissertation found the predictions to be inadequate. Upon inspection, the equations seemed to be inconsistent with the outlined procedure. The analytical equations were reformulated based on Lange’s stated procedure and the empirical equations were retained. The new formulations predicted blank shapes more accurately when compared to a one-step FEM simulation as shown in Table 2.2.

\[
\begin{align*}
    l_0 &= l_i + 2h + 2f - 2\Delta l_0 & \text{Blank Length} & \quad \text{(Equation 2.18)} \\
    w_0 &= w_i + 2h + 2f - 2\Delta w_0 & \text{Blank Width} & \quad \text{(Equation 2.19)} \\
    c_0 &= \left( \sqrt{\{0.5(l_0 - l_i) + r_i\}^2 + \{0.5(w_0 - w_i) + r_i\}^2} - r_0 ' \right)/2 & \text{Corner Chamfer} & \quad \text{(Equation 2.20)} \\
    r_0 &= \frac{c_0}{\sqrt{2}} & \text{Blank Radius} & \quad \text{(Equation 2.21)}
\end{align*}
\]

Where \( \Delta l_0 \), \( \Delta w_0 \), \( r_0 '' \), and \( r_0 ' \) are calculated from Lange's empirical equations (Appendix A.2).
Figure 2.42: Symbols used for rectangular pan analysis

<table>
<thead>
<tr>
<th></th>
<th>2&quot; DEEP PANEL</th>
<th>4&quot; DEEP PANEL</th>
</tr>
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Table 2.2: Comparison of blank shape predictions for a 12" by 15" rectangular panel with 1" flange

2.4.2 Computer Simulation

There are many commercially available finite element simulation codes that analyze sheet metal forming processes as shown in Table 2.3. Although FEM simulation is a good tool to analyze the sheet forming process, three issues are of current concern. First, computer simulations require a lot of engineering time and computing resources and an
experienced, well trained engineer to obtain reliable results. Second, the use of simple equations may be enough to conduct certain analyses and may be even be more advantageous than computer simulations. Third, add-on modules to commercial FEM programs that implement a feedback loop into the calculations (adaptive simulation) would be extremely useful to optimize the process.

Two types of FEM formulations are commonly used. In “one-step FEM”, the user inputs the part geometry and optional process conditions and the solver unfolds the part shape onto the binder surface. One-step FEM is computationally fast, can take into account material properties and deformation, and can account for process conditions such as BHF, drawbeads, friction, and bending if the user desires. Springback calculations are also included with many one-step FEM packages. One-step FEM does not simulate the deformation history, does not solve iterative calculations incrementally, and does not simulate the material/tool contact.

The second most commonly used FEM codes are “incremental” type codes which are based on dynamic explicit formulation. Incremental FEM simulates the sheet forming process in exactly the same way the actual process occurs. The user inputs the tool and material geometry, material properties, and boundary conditions (velocities, forces, symmetry, rigidity, etc.) The solver then calculates the movement of the tools, the contact of the materials and tools, friction at the interface, displacements of the nodes, strains of the material, and workpiece and tool stresses. The entire sheet forming process can be simulated including gravity/binder wrap, clamping, forming, trimming/piercing, flanging/hemming, and springback.

The one-step FEM software that will be used with this research is FAST_FORM3D from FTI Inc. (Ontario, Canada). An example of its use is shown in Figure 2.43. In this case study, a cab corner outer for a light truck was press formed using the rectangular blank as shown in Figure 2.43a. After full deformation, the blank would draw through the beads
as shown in Figure 2.43c. Drawing fully through the bead causes process instability and non-uniformity of the part strain which increases springback and decreases the formability window.

FAST_FORM3D was used to calculate a blank shape which would draw right to the outside edge of the bead at every point as shown in Figures 2.43b and 2.43d. Using the incremental FEM code Pam-Stamp (ESI Int’l - Paris, France) the original and optimized blank was simulated and is shown in Figure 2.44. These simulations show that the optimized blank improved the strain distributions significantly.

In another case study, Pam-Stamp was used to simulate a door outer panel that was in hard tool production. Figure 2.45 shows how splitting and distortion were predicted to occur on the part surface. Splitting did occur on the header of the door during physical tool tryouts thus confirming the predictions. In order to eliminate the splitting condition, some of the take up beads in the window cavity were removed.

![Figure 2.43: Optimal blank shape prediction for the cab corner outer panel using FAST_FORM3D (one-step FEM from FTI Inc.)](image-url)

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Figure 2.44: Improvement of strain distribution in the cab corner by optimizing the blank shape (Pam-Stamp from ESI Int’l - incremental simulation)

Figure 2.45: Prediction of splitting and distortions in a door outer panel (Pam-Stamp from ESI Int’l - incremental simulation)
<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
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<td>Pam-Stamp</td>
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</tr>
<tr>
<td>FAST_FORM3D</td>
<td>inverse theory</td>
<td>Sheet forming</td>
</tr>
</tbody>
</table>

Table 2.3: Commercially available FEM codes - their formulations and applications

2.4.3 Failure Prediction

Failure may occur in sheet metal parts in a number of ways including:

1. Fracture
2. Necking
3. Wrinkling
4. Distortions

5. Undesirable Surface Textures

For most strain paths, necking precedes fracture, therefore necking prediction is of greater concern (see Figure 2.46). Fracture may be observed as a split/tear (excessive stretching), a surface crack (excessive bending), or an edge failure (caused by an imperfection in the blanked edge).

Wrinkling or buckling is caused by compressive stresses and typically occurs on the flange of the part. Often it may not be a concern if the flange is trimmed as with many automotive parts. When the sheet experiences very low stresses, compressive or tensile, then distortions may occur.

Residual stresses may also cause geometric distortions in the part. Large scale distortions may take the form of highs or lows in the part surface or as oil canning (elastic instabilities). Small scale distortions may take the form of rabbit earing, pie crust, crow’s feet, or teddy bear ears.

Undesirable surface textures such as orange peel or stretcher strain markings may also occur during deformation. Orange peel consists of a rough surface appearance typically caused by the variation of flow stress properties of the various grains contained in the material. Two types of stretcher strains are observed. The first type is caused by discontinuous yielding at the yield point and is evidenced by irregular striations on the surface of the sheet. The second type of stretcher strain marking is caused by discontinuous yielding in the plastic region of the material and is evidenced by regular striations on the surface of the sheet.

Finite element simulation is currently limited when it comes to predicting the exact time of failure. This is demonstrated in Figure 2.47a. Clearly the cup has strained well
beyond the point of failure, but the deformation continues to be blindly calculated by the solver. Further, even though failure is evident, it is not clear exactly when it occurs.

Many failure criteria have been proposed in the past. The thinning in the part has been traditionally used to estimate proximity to failure and is demonstrated in Figure 2.47b. This is an approximate method, because the limit of thinning can vary with strain path. Biaxial strain has been proposed by Keeler (1965) and Goodwin (1968) to estimate failure in the form of a forming limit diagram (FLD) as shown in Figure 2.46. It has been shown by several researchers that the forming limit curve (FLC) is highly dependent on strain path as shown in Figure 2.48 (Arrieux, 1995). Further, the measurement of a FLC requires extensive and laborious experimentation. For steel, the following formula has been experimentally developed to calculate the FLD as a function of n-value and material thickness:

\[
FLD_0 = (105.02 + 69.885t)n_0
\]

Where \(n_0 = n\) if \(n > 0.22\), otherwise \(n_0 = 0.22\)

\[
e_1 = 0.53388(-e_2)^{0.59902} + FLD_0 \text{ for } e_2 < 0 \tag{Equation 2.22}
\]

\[
e_1 = 1.3941 \cdot e_2^{69.865} + FLD_0 \text{ for } e_2 > 0
\]

\[
e_1 = FLD_0 \text{ for } e_2 = 0
\]

Other failure criteria have been proposed based on examining the stress in the part rather than the strain. For example, it is noted that stress based fracture limits are insensitive to strain paths as shown in Figure 2.49 (Arrieux, 1995). The most notable feature of Figure 2.49 is the fact that the failure limit in biaxial stress space resembles a yield surface. This gives credence to the use of a stress based limit to predict failure based on yield criteria such a Tresca’s (normal stress limit), Von Mises (isotropic equivalent stress limit), or Hill’s (anisotropic and/or non-quadratic equivalent stress limit).

The previous failure criteria were based on instantaneous values of stress and strain. A failure criterion that considers the instantaneous stresses and the deformation history was proposed by Cockroft and Latham (1968):
\[ \dot{\varepsilon}_i \cdot \int_0^\sigma \frac{\sigma_1}{\bar{\sigma}} d\bar{\varepsilon} = C \]  

(Equation 2.23) (Crockcroft, 1968)

Where \( \bar{\sigma} \) is the equivalent stress and \( \sigma_1 \) is the first principle stress. The stresses are integrated along the entire strain path and failure is predicted to occur when the integral attains a finite value \( C \) (material constant) as measured from simple experiments such as a tensile test.

Figure 2.46: Various sheet failures shown on a forming limit diagram (Hosford and Caddell, 1993)
a) Failure without element deletion

b) Element deletion by thinning limit

Figure 2.47: Failure prediction in finite element simulation

Figure 2.48: Effect of strain path on the failure limit in biaxial strain space (Arrieux, 1995)

Figure 2.49: Effect of strain path on the failure limit in biaxial stress space (Arrieux, 1995)
2.5 Issues with Forming Aluminum Alloys

2.5.1 Product Design Considerations

Care must be taken in the design of aluminum stampings especially if the product was historically designed using steel. One of the first considerations to be taken into account is the fact that aluminum has one third the Young’s modulus of steel. Thus the final product stiffness will be reduced unless the product design is modified to account for this factor. Two possibilities are to increase the ribbing used in the product and to increase the part thickness. The stiffness of the final product tends to increase in proportion to the square of the thickness. Also, ribs tend to increase stiffness by increasing the section moment of inertia (Thiruvarudehelvan, 1996).

The reduction of Young’s modulus will result in an increase in the tendency for wrinkling, oil canning, and surface distortion. Flange wrinkling can typically be controlled by the use of a blank holder, but wrinkling/oil canning/distortions in the product or addendum region can be difficult to control. Increasing material thickness can improve these issues, but the best method is to increase the geometry in the problem area by introducing gainers, drawbars, ribs, or embosses. There will also be a proportional increase in springback due to the reduction of Young’s modulus. This can be offset by overcrowning the die geometry or by increasing the stretch in the final part.

The yield strength of aluminum alloys is less than that of steel. Consequently, the overall strength, dent resistance, energy absorption, and crash resistance of the panel will be less. Certain alloys such as 2000 and 6000 series alloys can be baked after forming to increase yield strength. Otherwise, good design must be employed to make up for this strength loss (Vreede, 1996).

Decreases in overall elongation and normal anisotropy are also typical in aluminum alloys. Bendability of aluminum may be an issue for many alloys as well. Part designers should be aware of minimum bend radii of the aluminum alloy to be used (Aluminum
Association, 1997). If minimum bend radii are not available from the material supplier, Figure 2.50 may be used. Figure 2.50 is a graph of minimum bend radius versus tensile reduction of area. If the reduction of area from a tensile test is known, an approximate minimum radius to thickness ratio may be obtained from this graph. If minimum bend radii limitations are not considered in the part design then cracking may be observed in the final part as shown in Figure 2.51. Hemming is also associated with bendability. If the material cannot be bent to a zero radius then the hem design must reflect this limitation. Figure 2.52 illustrates alternative hem designs for cases when flat hems cannot be used.

The reduction of the formability of aluminum must also be taken into consideration for the drawing and stretching of deep recesses. A corresponding decrease in the depth of the recess may be required to accommodate the formability of the aluminum. Further, aluminum alloys typically have lower forming limit diagrams (FLD) when compared with steel and this must be taken into account when designing dies for stamping of complex geometries.

One of the most important considerations in stamping aluminum alloys is the increased cost of the material when compared to steel. This can be offset by the design of robust production systems that produce very low scrap rates through the use of in process control of the blank holder force. Tailor welded blanks may also be used to increase material utilization, minimize assembly, and increase dimensional accuracy (Story, 1998; Wagoner, 1999).

2.5.2 Die and Process Design Considerations

Die and process design must be carefully considered in order to deal with the reduced formability window of aluminum. To ensure good product quality, the process must be optimized to ensure at least 2% minimum stretch throughout the part. This minimum value of strain is confirmed by Figures 2.10 and 2.11. Figure 2.10 shows that at strains
less that 2%, springback is greatly increased. Likewise, Figure 2.11 shows that 2% strain is required to ensure good dent resistance properties. Both graphs show that springback and dent resistance levels off at around 2% stretch.

![Graph showing bend radius to thickness ratio versus tensile reduction of area](image1)

**Figure 2.50:** Minimum bend radius to thickness ratio versus tensile reduction of area (Kalpakjian, 1991)

![Image showing cracking due to violation of minimum bend radius](image2)

**Figure 2.51:** Cracking due to violation of minimum bend radius (Livatyali, 1997)

![Alternative hem designs for aluminum](image3)

**Figure 2.52:** Alternative hem designs for aluminum (Livatyali, 1997)
The decrease in formability of aluminum can also be offset through the use of advanced die and process design and through the use of advanced technology (Ahmetoglu, 1996). The clever use of advanced addendum design has been used successfully to widen the formability margins so that complicated geometries may be formed from aluminum (Burk, 1996). The addendum is defined as the portion of the die between the binder and the trim line. The most typical addendum feature is the drawwall which is used to connect the binder surface to the part geometry. Other addendum features include the use of gainers and drawbars. The downside to increasing the addendum region is that addendum is typically engineered scrap and thus this method tends to increase scrap realized per part.

The use of advanced technologies such as blank holder force control, hydroforming, and warm forming may also be use to increase the formability window of aluminum alloys. The cost associated with this solution is the capital investment of the presses and equipment needed to implement these processes. Blank holder force control has been shown to increase drawability and process robustness. Similarly, hydroforming can increase formability, strain uniformity, strain hardening, and decrease tooling costs.

Warm forming by definition is the forming of material at a temperature between cold forming and hot forming. Typically hot forming is exhibited by temperatures just below the melting temperature of the material while cold forming is conducted at room temperature. Warm forming requires less energy, insulation, technology and logistics than hot forming and thus is an attractive process for difficult to form parts. By increasing the temperature of the aluminum sheet material, many advantages in terms of formability can be obtained. As shown in Figure 2.53, the flow stress of the material tends to decrease as temperature increases which thereby decreases forming loads. Further investigations have shown that increasing material temperatures tends to increase elongation, increase strain rate hardening, decrease ludering, and increase the forming limit curve (Holt, 1998).
This increase of material formability can be useful for forming deep recesses or complicated geometries. Warm forming requires an investment in equipment. An oven is needed to heat the incoming material and heater cores must be implemented into the tooling as shown in Figure 2.54 for the example of steel. Insulation must also be used to maintain die temperature efficiently. Further, different regions of the die require different levels to heat to ensure that formability is improved requiring expensive controls and electronics. In general, the binders should be heated for deep drawn parts and not heated for stretched parts. Tight radii should not be heated while flat regions or regions with low curvature should be heated (Ghosh, 1995). While warm forming offers advantages in improving the formability of aluminum alloys, it also increases the complexity of die design and process control.

During trimming and piercing operations, the production of slivers can cause problems. Slivering can be reduced by trimming at an angle that is not perpendicular to the sheet surface (Holt, 1998). This tends to decrease the shear stresses and increase the tensile stresses at the trim edge. This in turn tends to reduce the burr height which consequently reduces slivering. Since the knowledge base of aluminum forming is far less than that of steel, computer simulation will play a key role in the implementation of aluminum as shown in Figure 2.55. Decisions that were previously based on experience will be less reliable for aluminum, unless they are backed up with results from process simulation (Weinmann, 1995).

2.5.3 Material Considerations

During the stretching or forming operations of some metals, especially aluminum-magnesium alloys and some low carbon steels, visible localized yielding occurs which are commonly referred to as stretcher strain markings or luders lines. They are extremely undesirable because of their negative influence on the surface quality of the parts. This highly visible phenomenon cannot be concealed by painting and therefore poses a problem for outer body panels.
Two types of stretcher strains are observed. The first is called Type A ludering and is evidenced by irregular striations on the surface of the sheet (Figure 2.56a). The tensile test of a Type A ludering shows that discontinuous stretching of the material is observed at the yield point (Figure 2.56b). Type B ludering consists of regular striations on the surface (Figure 2.56c) and discontinuous stretching in the plastic region of a tensile test (Figure 2.56d).
Certain aluminum alloys, such as 6000 series, are less susceptible to stretcher strain markings. More precisely, stretcher strain markings tend to occur at room temperatures and at strain rates observed in typical press production. At temperatures above 100°C and below -50°C and at strain rates above 10 inches per second or below 0.1 inches per second, stretcher strains tend to reduce or disappear. Thus, stretcher strains occur in a window on a strain rate versus temperature map that is centered at typical forming conditions as shown in Figure 2.57 (Daehn, 1994).

Orange peel (Figure 2.58) is another surface defect associated with aluminum forming. Orange peel consists of a rough surface appearance typically caused by the variation of flow stress properties of the various grains contained in the material. The most convenient way to reduce orange peel is to decrease the grain size of the material (Hosford, 1993).

Surface issues are also important considerations in the forming of aluminum. Galling can be a problem, but can be eliminated by the use of good lubrication, well polished dies, and chrome plating. Otherwise, regular die polishing can be used to reduce buildup of galled material on the die surfaces.

The surface roughness of aluminum ($R_a$) ranges from 0.25 to 0.38 microns while steel ranges from 0.63 to 0.88. The smoother surface texture of aluminum tends to not trap lubricant as well as steel. Surface texturing of the aluminum sheet can be considered to improve lubrication entrapment, friction, and formability. The oxide layer on aluminum tends to improve friction at the tool-sheet interface for both lubricated and unlubricated cases (Smith, 1993).

Other issues that are associated with aluminum include corrosion resistance, age hardening, surface damage, surface texture changes during forming, issues with handling
associated with the non-magnetic nature of aluminum, and welding. Each of this issues warrant proper engineering consideration (Decaillet, 1990).

<table>
<thead>
<tr>
<th>a)</th>
<th>Type A ludging (Hosford, 1993)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b)</td>
<td>Discontinuous yielding - Type A</td>
</tr>
<tr>
<td>c)</td>
<td>Type B ludging (Wong, 1968)</td>
</tr>
<tr>
<td>d)</td>
<td>Discontinuous yielding - Type B</td>
</tr>
</tbody>
</table>

Figure 2.56: Various stretcher strain phenomena
Figure 2.57: Stretcher strain marking window of occurrence

Figure 2.58: Orange peel (Hosford, 1993)
CHAPTER III

RESEARCH PLAN

3.1 Rationale for the Proposed Research

The literature for deep drawing and stamping has been perused exhaustively and summarized in Chapter 2. Table 3.1 below summarizes the work done to analytically predict optimal BHF profiles. Brief comments on each investigator's work are also included. The last line of Table 3.1 summarizes analytical work proposed by the author of this dissertation and contrasts this approach to the other works.

In short, research is needed to improve upon the previous analytical investigations to predict optimal BHF profiles for deep drawing and stamping. The strategy is to start first with simple geometries, i.e. deep drawing of round cups and rectangular pans, and develop an analytical approach and computer program to predict optimal BHF trajectories in function of punch stroke. Based on the results of this first step, work will be extended to develop a method for estimating optimum BHF strategies in time and location for rectangular and asymmetric stampings using finite element analysis with feedback. We will refer to this approach as adaptive simulation.

The proposed analytical research will expand previous research in the following four major areas (details in Section 4.1):

- Equivalent stress will be used as the feedback parameter. Stress has been shown to be a good failure criterion due to its insensitivity to strain and stress path (Arrieux, 1995). The use of only one feedback will make the analysis simpler than previous works.
• Anisotropy of the material will be included in the analysis.
• The evolution of the wrapping of material around the die radius will be included in the analysis.
• The predictions will be extended to rectangular pan deep drawing.

Similarly, Table 3.2 summarizes the previous research involving the prediction of optimal BHF profiles by implementing feedback control into commercial FEM simulation packages (adaptive simulation). The proposed research will build upon what previous researchers have accomplished through the following (details in Section 4.2):
• Use binder gap (wrinkling), equivalent stress, thickness strain, and punch force as the feedback loop for time variable BHF.
• Expand the binder gap (wrinkling) method to predict optimal spatial patterns for location variable BHF. The author of this dissertation has not found any previous work concerning the prediction of optimal spatial patterns of the BHF.
• Round cups, rectangular pans, and asymmetric panels will be included in the analysis.

Table 3.3 summarizes previous research into experimental closed-loop BHF control. The proposed experimental research will build upon the work of previous researchers by accomplishing the following.
• Verification of the analytical and FEM predictions for optimal BHF profiles using round cups, rectangular pans, and asymmetric panels (fully asymmetric geometries have not been explored extensively in the laboratory).
• The physical BHF control system will be hydraulic, passive (does not use a pump and reacts to the press motion only), and closed-loop controlled (Shulkin, 1996). This will greatly reduce the cost of such systems and make implementation easier.
• The physical BHF control system will use tool displacement, pressure, and punch force as feedback parameters for the control algorithm.
<table>
<thead>
<tr>
<th>WORKER</th>
<th>TYPE OF WORK</th>
<th>FEEDBACK</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawai 1961</td>
<td>Analytical Round Cups</td>
<td>Wrinkle Criterion</td>
<td>Analysis does not include anisotropy and wrap angle</td>
</tr>
<tr>
<td>Manabe 1987</td>
<td>Analytical Round Cups</td>
<td>Punch Force</td>
<td>Analysis does not include anisotropy and wrap angle</td>
</tr>
<tr>
<td>Ahmetoglu 1996</td>
<td>Analytical Round Cups</td>
<td>Punch Force, Radial Stress, Thinning</td>
<td>Three feedback loops are unnecessary and difficult to implement</td>
</tr>
<tr>
<td>Thomas 1999 (Proposed)</td>
<td>Analytical Round Cups Rectangular Pans</td>
<td>Equivalent Stress</td>
<td>Stress fracture criteria, anisotropy, and wrap angle included. Only one feedback.</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of previous/current analytical work to predict optimal BHF profiles

<table>
<thead>
<tr>
<th>WORKER</th>
<th>TYPE OF WORK</th>
<th>FEEDBACK</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traversin 1996</td>
<td>FEM Simulation Round Cups</td>
<td>Punch Force Binder Gap</td>
<td>Did not include prediction of location variable BHF</td>
</tr>
<tr>
<td>Cao / Boyce 1994</td>
<td>FEM Simulation Round Cups</td>
<td>Wrinkle Criterion Major Strain</td>
<td>Major strain is a poor fracture criterion</td>
</tr>
<tr>
<td>Thomas (1997)</td>
<td>FEM Simulation Experimental Rectangular Pans</td>
<td>None</td>
<td>Trial and error is laborious</td>
</tr>
<tr>
<td>Shulkin (1998)</td>
<td>FEM Simulation Asymmetric Panels</td>
<td>BHP Distribution</td>
<td>Took into account tool elasticity, but does not consider material formability except thru trial &amp; error</td>
</tr>
<tr>
<td>Thomas 1999 (Proposed)</td>
<td>FEM Simulation Round Cups Rectangular Pans Asymmetric Panels</td>
<td>Binder Gap (Wrinkling), Equivalent Stress, Thickness Strain, Punch Force</td>
<td>Location variable BHF prediction is proposed.</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of previous and current FEM work to predict optimal BHF profiles

72
<table>
<thead>
<tr>
<th>WORKER</th>
<th>TYPE OF WORK</th>
<th>FEEDBACK</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kergen 1992</td>
<td>Experimental Round Cups</td>
<td>Punch Force Binder Gap</td>
<td>Binder gap feedback does not attempt to maximize stress in part.</td>
</tr>
<tr>
<td>Siegert 1998</td>
<td>Experimental Round Cups</td>
<td>Punch Force Binder Gap Friction Force Draw In</td>
<td>Based on time consuming constant BHF experiments</td>
</tr>
<tr>
<td>Doege 1995</td>
<td>Experimental 4 Side Asymmetric Spatial Control</td>
<td>Punch Force Spatial Control proportional to side length</td>
<td>Based on time consuming constant BHF experiments</td>
</tr>
<tr>
<td>Hardt 1993</td>
<td>Experimental Round Cups Square Asymmetric</td>
<td>Punch Force Thickening</td>
<td>Based on time consuming constant BHF experiments</td>
</tr>
<tr>
<td>Manabe 1995</td>
<td>Experimental Fuzzy Control Round Cups</td>
<td>Draw Ratio Thickening</td>
<td>Punch force is a poor fracture criterion</td>
</tr>
<tr>
<td>Osakada 1995</td>
<td>Experimental Round Cups</td>
<td>Thinning Thickening</td>
<td>Thinning is a poor fracture criterion</td>
</tr>
<tr>
<td>Thomas 1999 (Proposed)</td>
<td>Experimental Round Cups Rectangular Pans Asymmetric Panels</td>
<td>Closed-loop control. analytical, numerical, and empirically predicted BHF profiles.</td>
<td>Verify predicted time and location variable BHF profiles using a passive, hydraulic, closed and open-loop BHF control system. Time and expense will be saved.</td>
</tr>
</tbody>
</table>

Table 3.3: Summary of previous and current experimental work to predict optimal BHF profiles

3.2 Research Objectives

The objectives of the proposed research are to:

- Develop a part and process design methodology for the deep drawing and stamping of sheet metal parts that will lead to a robust process with improved part quality.
• Develop a mathematical model and computer software that allows engineers to calculate forming forces, formability limits, required tool geometry, and optimal BHF profiles for simple part geometries such as round cups, rectangular pans, U-channels, hemispherical shells, and asymmetric panels.

• Develop a module for commercial finite element method (FEM) programs that implements a feedback loop into the calculations (adaptive simulation) in order to determine optimal BHF time trajectories and spatial patterns for general complex geometries.

• Develop computerized tools that provide engineers with the effect of process parameters on part quality (sensitivity data) for various simple tool geometries using laboratory experiments and computer simulations.

The scope of this dissertation consists of:

• Sheet metal parts ranging from cylindrical shells to complex automotive body panels.

• Materials ranging from drawing quality steel, high strength steel, dent resistant steel, and aluminum alloys (2000, 3000, 5000, and 6000 series).

3.3 Research Approach

This research will be completed in six phases as follows:

Phase 1: Conduct Literature Review

Phase 2: Build New Laboratory Tooling

Phase 3: Develop Analytical Models to Predict Optimal BHF Profiles for Simple Geometries

Phase 4: Develop a Module for a Commercial FEM Code to Predict Optimal BHF Profiles for Complex Geometries (Adaptive Simulation)

Phase 5: Conduct Experiments and Validate Models

Phase 6: Develop Sheet Forming Design Methodology

Phase 7: Deliver Research Results
3.4 Research Plan

A detailed description of the seven phases of this research is given.

*Phase 1: Conduct Literature Review*

The objective of this phase is:

- To conduct a literature review to understand the current industrial part and process design methodology for sheet metal stampings.

The tasks of this phase are:

1.1: Conduct a literature review of deep drawing and stamping.

1.2: Outline the current design process from concept to production.

1.3: Identify the tools that are needed by engineers to improve the current design process. Determine the format of these tools and when in the design process they are needed.

1.4: Collect all available part and process design rules from literature and the current research and put them in a computer module for easy use by an engineer.

*Phase 2: Build New Laboratory Tooling*

The objective of this phase is:

- To design, validate, build, and test new laboratory tooling.

The tasks of this phase are:

2.1: Design, validate, build, and test a new rectangular pan deep draw tooling for the purpose of investigating time and location variable BHF control (see Figure 3.3).

2.2: Design, validate, build, and test a new asymmetric panel stretch-draw tooling for the purpose of investigating the automotive outer body panel stamping process (see Figure 3.7).
Phase 3: Develop Analytical Models to Predict Optimal BHF Profiles for Simple Geometries

The objective of this phase is:

- To develop analytical models of the deep drawing of round cups and rectangular pans in order to calculate optimum BHF profiles and to create computer based tools using these derivations.

The tasks of this phase are:

3.1: Develop equations for calculating optimal BHF profiles for round cup and rectangular pan deep drawing. These derivations are included in Section 4.1.

3.2: Implement these derivations and other useful equations into a computer module. This sheet forming design system will include the following types of calculations:

- Round Cups and Rectangular Pan Deep Drawing
- Optimal BHF Time Profiles
- Minimum and Maximum Constant BHF
- Load Versus Stroke
- Limiting Draw Ratio
- Drawbead Forces and Geometry
- Blank Shapes
- Forming Limit Diagrams

Phase 4: Develop a Module for a Commercial FEM Code to Predict Optimal BHF Profiles for Complex Geometries (Adaptive Simulation)

The objective of this phase is:

- To implement a feedback loop into a commercially available analysis software (adaptive simulation) in order to determine optimum BHF time profiles and spatial patterns for complex geometries.
The tasks of this phase are:

4.1: "Manually" control an FEM simulation at discrete time intervals in order to prove the concept of implementing a feedback loop for the prediction of optimal BHF time profiles and spatial patterns for round, rectangular, and asymmetric parts.

4.2: Upgrade the commercially available FEM simulation software Pam-Stamp with a closed-loop controller which will allow the prediction of optimal BHF time and location variable profiles for any general geometry and process. The methodology is outlined in Section 4.2.

**Phase 5: Conduct Experiments and Validate Models**

The objectives of this phase are:

- To validate the analytical tools with extensive laboratory experiments.
- To test these analytical tools in an industrial setting.

A series of experiments will be conducted at the ERC/NSM laboratories. These experiments will be conducted in a 160 ton hydraulic Minster press with numerically controlled (NC) die cushion (see Figure 3.1 and Table 3.4). The tasks of this phase are:

5.1: Round Cup Deep Drawing Experiments (6” diameter, 7” deep, see Figure 3.2)

- Conduct full sensitivity analysis with experiments and simulations in order to determine to the effect of all relevant process parameters on product quality.
- Verify predicted time variable BHF profiles from analytical equations and FEM simulations using the NC press cushion (see Figure 3.1).
- Verify the blank shape prediction of analytical equations and one-step FEM.
- Investigate the formability of aluminum 6111-T4, AKDQ, bake hard, and high strength steel.
5.2: Rectangular Pan Deep Drawing Experiments (12” by 15”, 7” deep, see Figure 3.3 through 3.6)

- Conduct full sensitivity analysis with experiments and simulations in order to determine to the effect of all relevant process parameters on product quality.
- Verify predicted time variable BHF profile from analytical equations using the NC press cushion (see Figure 3.1).
- Verify predicted time and location variable BHF profiles from FEM simulations using the hydraulic BHF control system (see Figure 2.32).
- Verify the blank shape prediction of analytical equations and one-step FEM.
- Investigate the formability of aluminum alloys 2008-T4, 3003-H13, 6111-T4, and AKDQ steel.

5.3: Asymmetric Panel Stretch-Draw Experiments (17” by 24”, 3” deep, see Figure 3.7 through 3.11)

- Conduct full sensitivity analysis with experiments and simulations in order to determine to the effect of all relevant process parameters on product quality.
- Determine the interaction of BHF, drawbeads, and stopblocks (see Figure 3.7).
- Determine the effect of pad pressure on distortions caused by embossing (see Figure 3.8 and 2.9).
- Investigate the formability of AKDQ steel.

5.4: Industrial Validation

- Test the tools developed in this project in an actual industrial setting. The following phases of the current design process will be tested using the proposed design methodology:
  1. Product Design – Light Weight Closure and Cab Corner Case Study
  2. Soft Tooling Tryout - Deck Lid Case Study
  3. Hard Tooling Tryout - Fender and Door Outer Case Study

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4. Production - Wheel Housing Case Study

**Phase 6: Develop Sheet Forming Design Methodology**

The objective of this phase is:

- To develop a sheet forming design methodology and the associated tools needed to aid an engineer in the design of better sheet metal parts and processes.

The tasks of this phase are:

6.1: To outline a new concept to production process utilizing these tools.

6.2: To develop educational modules which will instruct the engineer on the use of the proposed design methodology and associated tools. The modules will include:

- Sheet Forming Design Methodology
- Fundamentals of Deep Drawing and Stamping
- Presses and Equipment
- Tools and Dies
- Formability and Failure of Materials
- Friction and Lubrication
- Product Quality in Sheet Forming
- New Technologies in Sheet Forming (BHF control, hydroforming, tailor welded blanks, light weight materials, warm forming, surface texturing)
- Database of Sensitivity Data (bending, flanging, hemming, drawbeads, U-channels, round cups, rectangular pans, asymmetric panels)
- The Finite Element Method and Simulation Methodology (incremental and one-step FEM)
- Industrial Case Studies (doors, deck lid, cabin inner, fender, roof, wheel housings, cab corner)
Phase 7: Deliver Research Results

The objective of this phase is:

- To develop instructional modules to transfer the results of this study for academic teaching and for industrial training purposes.

The tasks of this phase are:

7.2: Publish in peer reviewed journals
7.3: Publish in trade journals
7.4: Present at conferences

Figure 3.1: 160 ton hydraulic Minster press with die cushion and rectangular tooling
<table>
<thead>
<tr>
<th>Type</th>
<th>Minster Tranemo DPA-160-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slide Force</td>
<td>160 metric tons (176.4 tons)</td>
</tr>
<tr>
<td>Cushion Force</td>
<td>100 metric tons (110.3 tons)</td>
</tr>
<tr>
<td>Ejector Force</td>
<td>15 metric tons (16.5 tons)</td>
</tr>
<tr>
<td>Slide Speed</td>
<td>90 mm/s maximum (3.54 in/s)</td>
</tr>
<tr>
<td>Total Daylight</td>
<td>800 mm (31.496&quot;)</td>
</tr>
<tr>
<td>Slide Stroke</td>
<td>500 mm (19.685&quot;)</td>
</tr>
<tr>
<td>Cushion Stroke</td>
<td>190 mm (7.480&quot;)</td>
</tr>
<tr>
<td>Ejector Stroke</td>
<td>250 mm (9.843&quot;)</td>
</tr>
<tr>
<td>Platen Size</td>
<td>1000 x 1000 mm (39.370&quot; x 39.370&quot;)</td>
</tr>
</tbody>
</table>

Table 3.4: 160 ton hydraulic Minster press specifications

![Image of hydraulic press](image1)

6" Diameter Punch
Deep drawing/stretching
Flat and dome punches
Multiple piece blank holder

Insertable Lockbeads
Cushion/Nitrogen BHF
Six cylinder locations
Punch load cell

Figure 3.2: Round cup deep draw tooling
Figure 3.3: Rectangular tooling with hydraulic BHF control system and insertable drawbeads

Figure 3.4: Rectangular pan (5" depth, 50 tons BHF, AKDQ steel)

Figure 3.5: Various part geometries of the rectangular tooling

12" by 15" Cavity
7" Draw Depth
Insertable Drawbead
Interchangeable Punches
Cushion/Nitrogen/Hydraulic
8 Cylinder Locations
Punch Load Cell
**Figure 3.6:** Minster press with rectangular tooling and hydraulic BHF control system

**Figure 3.7:** Asymmetric tooling with drawbeads, insertable emboss, adjustable stop blocks, and nitrogen pad

<table>
<thead>
<tr>
<th>17” by 24” Cavity - 3” Draw Depth</th>
<th>Interchangeable Emboss Inserts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully non-symmetric</td>
<td>Nitrogen Pad Action</td>
</tr>
<tr>
<td>Curved Binder - Doubly Curved Punch</td>
<td>Drawbeads (Stretch-Draw)</td>
</tr>
</tbody>
</table>

**Figure 3.8:** Nitrogen pad to reduce panel distortion due to embossing
Figure 3.9: Minster press with asymmetric tooling

Figure 3.10: Asymmetric panel with oval emboss (AKDQ steel, 100 tons BHF)

Figure 3.11: Various emboss geometries of the asymmetric tooling
CHAPTER IV

ANALYTICAL AND NUMERICAL MODELING
OF DEEP DRAWING AND STAMPING

4.1 Deep Drawing of Basic Geometries – Predicting Optimal BHF Profiles

4.1.1 Conceptual Approach

In order to determine the optimum variation of the BHF in function of time for round cup deep drawing, the drawing load will be mathematically derived in terms of the process parameters. Once the drawing load is known, the equations will be solved for BHF. The final step will be to apply a failure criterion which involves the drawing load. This will completely solve the equations for BHF. These equations will then be adapted to predict optimal BHF profiles for deep drawing of a rectangular pan.

Siebel (1955) developed a closed form solution for the drawing load of round cups as explained in Section 2.4.1. These equations did not take into account material anisotropy or the evolution of material wrap around the die radius. The current work will take these into account so that the drawing load can be calculated more accurately.

Further, previous researchers used rather unreliable failure criteria as part of their analyses (see Sections 2.3.4, 2.4.3 and 3.1). Equivalent stress will be used as the failure criterion because of its insensitivity to stress and strain path (Arrieux, 1995). Anisotropy and thinning will also be included to improved upon Siebel’s failure criterion. This should help to ensure the accuracy of the BHF profile that is predicted.
4.1.2 Round Cup Deep Drawing - Analytical Derivations

Siebel divided the round cup geometry into four deformation zones: 1) radial drawing in the flange, 2) bending at the die radius, 3) friction in the flange, and 4) friction at the die radius. He developed equations for the required forces for each of these sections and then summed them to obtain the drawing load. The following derivations are based on the work of Siebel (1955). The author of this dissertation has made various improvements as was previously proposed in order to increase the accuracy of the predictions.

Siebel (1955) analyzed the radial drawing in the flange as follows using the model and conventions in Figures 4.1 and 4.2 (symbols are given in Figure 2.40 and the Nomenclature section). He assumed that no thickening occurred in the flange.

Radial Direction:

\[(\sigma_r + d\sigma_r) (r + dr) d\beta t_0 - \sigma_r r d\beta t_0 + 2|\sigma_r| t_0 dr \sin\left(\frac{d\beta}{2}\right) = 0\]

(Equations 4.1) (Siebel, 1955)

Replace \(\sin\left(\frac{d\beta}{2}\right)\) with \(\frac{d\beta}{2}\) and neglect product of differentials.

\[d\sigma_r = - (\sigma_r - \sigma_f) \frac{dr}{r}\]

At this point, Siebel uses an isotropic yield criterion. In order to introduce anisotropy, the author of this dissertation has implemented the work of Leu (1997).

From Leu (1997), without any thickness strain in the flange and with Hill's quadratic normal isotropic yield criterion we obtain:

\[\sigma_r - \sigma_f = \frac{2(1 + \bar{r})}{1 + 2\bar{r}} \sigma\]

We substitute into Siebel's work:

\[d\sigma_r = - \sqrt{\frac{2(1 + \bar{r})}{1 + 2\bar{r}}} \sigma \frac{dr}{r}\]

Integrate:

\[\int_{\sigma_r = 0}^{\sigma_r} d\sigma_r = - \sqrt{\frac{2(1 + \bar{r})}{1 + 2\bar{r}}} \int_{r = 0}^{r} \sigma \frac{dr}{r}\]

\[\sigma_r (r) = \frac{2(1 + \bar{r})}{1 + 2\bar{r}} \sigma_f \ln \left(\frac{r_0}{r}\right)\]

Where \(\sigma_f\) is the average flow stress in the flange.
Figure 4.1: Stress conditions in the cup flange and wall (Crowley, 1998)

Figure 4.2: Siebel's radial drawing model to analyze flange deformation (Lange, 1985)
The previous case was derived without considering the additional restraint caused by the blank holder force. When the BHF is incorporated into the derivations of Equation 4.2, an additional term is obtained. Siebel reasoned that the radial stress increase due to friction was proportional to the blank holder pressure \( (p_b) \) and the coefficient of friction \( (\mu) \) and inversely proportional to the sheet thickness \( (t) \).

\[
\sigma_r (r) = \sqrt{\frac{2(1 + \bar{r})}{1 + 2\bar{r}}} \sigma_r \ln \left( \frac{r_o}{r} \right) + 2\mu (r_o - r) \frac{p_b}{t} 
\]  \hspace{1cm} \text{(Equation 4.3)}

Siebel also derived the friction around the die radius as follows. The model and conventions used are shown in Figure 4.3 which is essentially the rope-pulley friction model. The exact derivations are included in Appendix A.1. The final solution is shown below.

\[
\sigma_z = \sigma_r e^{\mu \alpha} \]  \hspace{1cm} \text{(Equation 4.4)}

Where \( \sigma_r \) is the radial stress at the entrance of the die radius and \( \sigma_z \) is the radial stress at the exit of the die radius.  \hspace{1cm} \text{(Siebel, 1995)}

Figure 4.3: Model for friction at the die radius (Lange, 1985)
Siebel’s derivations for bending around the die radius using an isotropic yield function are shown below. The physical model and conventions that he used are shown in Figure 4.4. He assumed that the bending is plane strain due to the fact that the ratio of the punch diameter to die radius is large. Also Siebel assumed that the sheet conforms to the full 90° arc of the die radius.

\[
W_b = M_b \alpha = F_1 r_d \alpha \quad \Rightarrow \quad F_1 = \frac{M_b}{r_d} \quad \text{(Equations 4.5)}
\]

(Siebel, 1995)

At this point, the author of this dissertation implements the work of Wang (1993) in order to take anisotropy into account.

From Wang (1993), plane strain bending and Hill’s quadratic normally anisotropic yield criterion:

\[
\sigma_h = \frac{1 + \tilde{r}}{\sqrt{1 + 2\tilde{r}}} \tilde{\sigma}
\]

Assume rigid plastic material:

\[
M_b = \frac{1 + \tilde{r}}{\sqrt{1 + 2\tilde{r}}} \frac{\sigma_{wt}^2}{4} \quad \text{(w = width of bent sheet)}
\]

Combine with Siebel’s work:

\[
F_i = \frac{1 + \tilde{r}}{\sqrt{1 + 2\tilde{r}}} \frac{\sigma_{wt}^2}{4 r_d}
\]

Double for bending and unbending and \( w = \pi d_w \):

\[
F_b = \frac{1 + \tilde{r}}{\sqrt{1 + 2\tilde{r}}} \frac{\pi \sigma_{wt}^2}{2 r_d}
\]

The author of this dissertation now introduces the bend angle \( \alpha \) into the bending force equation as a proportional multiplier.

\[
F_b = \frac{1 + \tilde{r}}{\sqrt{1 + 2\tilde{r}}} \frac{\alpha \sigma_{wt}^2}{r_d} \quad \text{(Equation 4.7)}
\]
Manabe (1997) derived the wrap angle ($\alpha$) for any draw depth and tooling configuration as shown below using the model shown in Figure 4.5.

$$\alpha = -2 \tan^{-1} \left\{ \frac{(c + r_p + r_d) - \sqrt{(c + r_p + r_d)^2 + (d - r_p - r_d)^2} - (r_p + r_d)^2}}{d - 2(r_p + r_d)} \right\}$$

(Equation 4.8) (Manabe, 1997)
Combining Equations 4.2, 4.3, 4.4, and 4.7, an expression for the drawing load \((F_d)\) is found. Please note that this equation takes anisotropy \((\tau)\) and wrap angle \((\alpha)\) into account, unlike Siebel’s (1955) equation (see Equation 2.12).

\[
F_d = (\pi d_w t_0) \left[ e^{\mu\alpha} \left( \sigma_f \ln \frac{d_f}{d_w} \sqrt{\frac{2(1+\tau)}{1+2\tau}} \right) + \left( \frac{2\mu F_b}{\pi d_f t_0} \right) \right] + \left( \sigma_d \frac{\alpha d_0}{\pi r_d} \frac{1+\tau}{\sqrt{1+2\tau}} \right)
\]

(Equation 4.9)

Now that we have a closed form solution for the drawing load of the round cup deep drawing process, we solve this equation for the blank holder force \((F_b)\). Solving for BHF has only been done by one other researcher namely Manabe (1987).

\[
F_b = \left[ \left( \frac{F_d}{\pi d_w t_0} \right) - \left( e^{\mu\alpha} \left( \sigma_f \ln \frac{d_f}{d_w} \sqrt{\frac{2(1+\tau)}{1+2\tau}} \right) - \left( \sigma_d \frac{\alpha d_0}{\pi r_d} \frac{1+\tau}{\sqrt{1+2\tau}} \right) \right) \right] \left( \frac{\pi d_f t_0}{2\mu} \right)
\]

(Equation 4.10)

In order to calculate the instantaneous flange diameter \((d_f)\) and the average flow stress in the flange \((\sigma_f)\) and die radius \((\sigma_d)\) please refer to Appendix A.1. In order to calculate the wrap angle \((\alpha)\), we use Equation 4.8.

Now, the only unknown parameter on the right side of Equation 4.10 is the drawing load \((F_d)\). We obtain this by utilizing a failure criterion that was proposed by Chiang and Kobayashi (1966). This failure criterion calculates the maximum drawing load to avoid failure in the cup. Chiang’s criterion takes into account the anisotropy and thinning of the sheet material. Chiang utilized Holloman’s flow stress laws to derive this criterion. The author of this dissertation has implemented Swift’s hardening law as shown below.

Starting from Hill’s plane stress normally anisotropic quadratic yield function (Wagoner, 1997):

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Plane Strain: \( d\varepsilon_2 = 0 \Rightarrow \sigma_2 = \frac{\bar{r}}{\bar{r} + 1} \sigma_1 \)

Assume proportional path: \( \bar{\varepsilon} = \frac{\bar{r} + 1}{\sqrt{2\bar{r} + 1}} \varepsilon_1 \)

Substitute into Hill’s equivalent stress formula: \( \bar{\sigma} = \frac{\sqrt{2\bar{r} + 1}}{\bar{r} + 1} \sigma_1 \)

Instability Criterion for Swift Power Law \( \bar{\sigma} = K(\bar{\varepsilon} + \bar{\varepsilon}_0)^n \)

For a tensile test: \( \varepsilon_u = n - \varepsilon_0 \)

Combining to obtain plane strain criterion: \( \bar{\varepsilon}_u = \frac{\bar{r} + 1}{\sqrt{2\bar{r} + 1}} (n - \bar{\varepsilon}_0) \)

Substitute into Swift’s Law: \( \bar{\sigma}_u = K \left[ \frac{\bar{r} + 1}{\sqrt{2\bar{r} + 1}} (n - \bar{\varepsilon}_0) - \bar{\varepsilon}_0 \right]^n \) \hspace{1cm} (Equations 4.11)

Calculate the thickness at the failure zone

Volume Constancy: \( \varepsilon_3 = -\varepsilon_1 \Rightarrow \ln \frac{t}{t_0} = -\frac{\sqrt{2\bar{r} + 1}}{\bar{r} + 1} \bar{\varepsilon} \)

\( t = t_0 \exp \left( -\frac{\sqrt{2\bar{r} + 1}}{\bar{r} + 1} \bar{\varepsilon} \right) \Rightarrow t = t_0 \exp (\bar{\varepsilon}_0 - n) \)

Calculate Critical Load

\( F_{cr} = \pi d_w t_0 \exp (\bar{\varepsilon}_0 - n) K \left[ \frac{\bar{r} + 1}{\sqrt{2\bar{r} + 1}} (n - \bar{\varepsilon}_0) - \bar{\varepsilon}_0 \right]^n \frac{\bar{r} + 1}{\sqrt{2\bar{r} + 1}} \)

### 4.1.3 Rectangular Pan Deep Drawing – Adaptation of Equations

To expand this work to rectangular pans, we will use the equivalent blank method as outlined in Section 2.4.1.2. Essentially, equivalent round blanks and tool geometries are calculated from the rectangular blanks and tool geometries based on equal areas as follows (symbols are given in Figure 2.42 and the Nomenclature section):

\( d_0^* = \sqrt{\frac{4l_0 w_0}{\pi}} \) \hspace{1cm} (Equation 4.12)

This method works extremely well for predicting load versus stroke curves for rectangular pans as will be shown in Section 4.1.4. This method does not work well for predicting the optimal BHF profiles. This is due to the fact that the wall stresses are not
distributed uniformly around the rectangular panel. In fact, the wall stresses are primarily concentrated in the corners of the rectangular pan. Therefore, to account for this phenomenon, the failure criterion will estimate the maximum punch load for the rectangular pan by assuming a round cup of diameter equal to twice the corner radius of the pan.

4.1.4 Computerization

The equations of Section 4.1.3 have been programmed into a Microsoft Excel spreadsheet. Excel was chosen because it is nearly a full featured programming environment with double precision, conditional arguments, and iterative calculations available. Excel also has a built in user interface that is familiar to most engineers. Thus, the development time and the learning curve are greatly reduced.

Instructions on the use of this spreadsheet are included in Appendix B. The opening page of the spreadsheet (or sheet forming design system) instructs the user on where to find the various calculations and how to use the module. Each sheet contains a user interface in which the user inputs the material data and tool geometry. The software then calculates various process conditions including loads, strains, stresses, geometry, and BHF profiles. A sample BHF profile from this package is shown in Figure 4.6.

4.1.5 Validation of Analytical Model

A complete validation of the analytical work will be conducted as a part of this dissertation. Some validation has been conducted already as a part of the development work. Since experiments have not been conducted in regards to the BHF predictions yet, data from the literature has been used in this validation. First, notice that the shape of the predicted BHF profile in Figure 4.6 is similar to the shape of Kergen’s and Siegert’s experimentally measured BHF profiles (Figures 2.33 to 2.34). This similarity gives confidence to this approach.
Figure 4.6: Sample BHF profile as calculated by the sheet forming design system (aluminum 6111-T4, 0.040" thickness, 2.17 LDR)

Figures 4.7 and 4.8 shows a comparison of the predicted load/stroke curve for Siebel’s formulation and the new formulation against measured data from an experiment conducted by Ahmetoglu (1996) for round cup deep drawing. Good agreement is observed between predictions and experiments as shown by the graphs. Clearly, this agreement is extremely important to the prediction of optimal BHF profiles.

Figure 4.9 shows a comparison of measured and predicted (Siebel’s and the new formulation) load stroke curves for the rectangular pan deep drawing of aluminum alloy 3003-H13 (conducted by the author of this dissertation). Again, the agreement was good, even with the assumption of equivalent blank and tool geometry. Further, in all three comparisons the new formulation improves the prediction capability when compared with Siebel’s prediction.
Figure 4.7: Comparison of analytical predictions with experimental data for round cup deep drawing of aluminum 1100-O (Ahmetoglu, 1996)

Figure 4.8: Comparison of analytical predictions with experimental data for round cup deep drawing of high strength steel (Ahmetoglu, 1996)
Figure 4.9: Comparison of analytical predictions with experimental data for rectangular pan deep drawing of 3003-H13 aluminum

4.1.6 Fracture Prediction

For the purpose of developing a simple and effective failure criterion, the following procedure was developed. Failure criteria that were previously proposed by other researchers were analytically evaluated and compared to forming limit diagrams. FLDs are the best available empirical failure criteria so it makes sense to use them as a benchmark. The following assumptions were used in the analysis.

- Normal anisotropy
- Plane stress
- Hill’s yield function
- Proportional strain paths

The following failure criteria were evaluated:

\[
\bar{\sigma} = \bar{\sigma}_U
\]

\[
\dot{\varepsilon}_1 \int \frac{\sigma_1}{\sigma} d\bar{\varepsilon} = C \tag{Equation 4.13}
\]
The value $C$ in the Crockroft and Lantham criterion can be evaluated with a tensile test. Using the above assumptions and the additional assumption of uniaxial stress in the tensile test, the integrand becomes unity and the value $C$ becomes exactly equal to the strain in the axial direction at failure:

$$C = \varepsilon_1 \bigg|_{f}$$  \hspace{1cm} (Equation 4.14)

This simple result will be useful later. One problem with this development is the assumption of proportional strain paths which is a good assumption in a tensile until necking begins and is increasingly poor thereafter. Since failure proceeds necking quickly, the final result is estimated to be within 10% of actual, thus making the assumption reasonable.

Now, we find the biaxial strain which satisfies each of the failure criteria above. The same assumptions are made and in each case the integrand becomes constant functions of material parameters. The following results are obtained:

\begin{align*}
\text{Crockroft & Lantham :} & \quad \varepsilon_1 = \frac{C \varphi}{\delta} \\
\text{Hill's Function :} & \quad \varepsilon_1 = \frac{\varepsilon_\nu}{\delta} \\
\end{align*}

(Equations 4.15)

Where $\beta, \lambda, \varphi, \delta$ are given as:

\begin{align*}
\beta &= \frac{\varepsilon_2}{\varepsilon_1} \\
\lambda &= \frac{\sigma_2}{\sigma_1} = \frac{\beta + \bar{r} + \bar{r} \beta}{1 + \bar{r} + \bar{r} \beta} \\
\varphi &= \frac{\bar{\sigma}}{\sigma_1} = \sqrt{1 + \lambda^2 - \frac{2\bar{r} \lambda}{1 + \bar{r}}} \\
\delta &= \frac{\varepsilon}{\varepsilon_1} = \sqrt{\frac{(1 + \bar{r})^2}{(1 + 2\bar{r})} \left[ 1 + \beta^2 + \frac{2\bar{r} \beta}{(1 + \bar{r})} \right]} \\
\end{align*}

(Equations 4.16)
These results are plotted in Figure 4.10 and 4.11. It is observed that both criteria tend to underestimate fracture and do not represent the shape of the curve either. I would like to mention that FLDs are measured with approximately constant strain ratio tests, which makes the assumption good until necking occurs as discussed previously.

Once this development was complete, it was relatively easy to find the combination of material constants which would create a curve that is shaped similarly to the FLD. The procedure was then reversed to calculate the actual failure criterion:

\[
\int \frac{\sigma}{\bar{\sigma}} d\varepsilon_i = C \quad \text{(Equation 4.17)}
\]

\[
\varepsilon_i = C \varphi
\]

This new failure criterion is shown in Figure 4.12. The shape and position are strikingly similar to the FLD. Essentially the proposed criterion is similar to Crockroft and Lantham, but the path integral is taken along \( d\varepsilon_i \) rather than \( d\bar{\varepsilon} \). This difference is small, but the effect is large. The author proposes that the reason for this observation may have to do with failure being more a function of \( \varepsilon_i \) than \( \bar{\varepsilon} \), but it is not known why.

\subsection{4.1.7 Correlation of LDR and \( \bar{\varepsilon} \)}

The mechanism involved in the effect of \( \bar{\varepsilon} \) on drawability has already been established in Section 2.1.3 of this dissertation. Whiteley (1960) conducted an experimental and analytical investigation to correlate normal anisotropy (\( \bar{\varepsilon} \)) with deep drawability. The investigation consisted of round cup deep drawing experiments with a variety of materials of various \( \bar{\varepsilon} \)-values. For each of these materials he experimentally determined a limiting draw ratio.
Figure 4.10: Comparison of Hill's failure criterion with an FLD

Figure 4.11: Comparison of Crockroft and Lantham's failure criterion with an FLD
Whiteley then derived an analytical formula relating the LDR to $\bar{r}$ for round cups. The geometric conventions of his analysis are shown in Figure 4.13. The assumptions he used were:

- Deformation only occurs in flange
- Failure only occurs in wall (fracture)
- No friction ($\mu=0$)
- No bending (membrane analysis)
- No strain hardening ($n=0$)
- Plane stress and plane strain in wall ($\sigma_z=0$, $\varepsilon_y=0$)
- No thinning in flange ($\varepsilon_z=0$)
- Normal anisotropy / planar isotropy

The intermediate results of his analysis are shown below. In words, Whiteley showed that the natural logarithm of LDR is equivalent to the ratio ($\beta$) of flow stresses in the wall ($\sigma_w$) and in the flange ($\sigma_f$). His equation included an efficiency factor ($\eta$) to account for bending and friction losses.
\[
\ln(LDR) = \eta \beta \\
\text{where: } LDR = \left( \frac{d_0}{d_1} \right)_{\text{max}} \\
\text{and: } \beta = \frac{\sigma_w}{\sigma_f}
\] (Equations 4.18) (Whiteley, 1960)

The next step in Whiteley's analysis was to calculate \( \beta \) (flow stress ratio) in terms of \( \bar{r} \) and other material constants using various yield criteria. Whiteley's analysis included the Von Mises isotropic and Hill quadratic anisotropic yield criteria as shown below. Hosford (1993) then expanded Whiteley's work by implementing a yield function based on crystallographic projections as shown below. The author of this dissertation then implemented Hosford's and Hill's non-quadratic anisotropic yield functions as shown below. The author would like to acknowledge Prof. R. Wagoner of The Ohio State University (Columbus, Ohio) for suggesting this analysis (Wagoner, 1997).

**Von Mises:** \( \beta = 1 \) (Equations 4.19) (Whiteley, 1960)

**Hill Quadratic:** \( \beta = \sqrt{\frac{(\bar{r} + 1)}{2}} \)

**Hosford's Microstructural:** \( \beta = \left( \frac{2\bar{r}}{\bar{r} + 1} \right)^{0.27} \) (Hosford, 1993)

**Hosford's Non-Quadratic:** \( \beta = \frac{(2 + 2^M \bar{r})^{\frac{1}{M}}}{\left[ 2 + 2^M \bar{r}^{\frac{1}{M}} + \bar{r} \right]^{\frac{1}{M}}} \) (Equation 4.20)

**Hill's Non-Quadratic:** \( \beta = \frac{(2\bar{r} + 1)^{\frac{1}{M}} \left[ 2\bar{r} + 1 \right]^{\frac{1}{M}} + 1}{2 \left[ 2\bar{r} + 1 + \left[ 2\bar{r} + 1 \right]^{\frac{1}{M}} \right]^{\frac{1}{M}}} \) (Equation 4.21)

By substituting these values of \( \beta \) into Equation 4.18 one can relate LDR to \( \bar{r} \) and several other material constants. These equations are plotted in Figure 4.14 along with the
experimental data. Whiteley proved that the experimental data does show a statistically significant correlation between $\bar{r}$ and LDR. The various equations exhibit varying levels of agreement with Hill's non-quadratic providing the best agreement.

Figure 4.13: Geometric conventions for Whiteley's analysis

Figure 4.14: Comparison of experimental measurements and analytical predictions of the correlation of $\bar{r}$ and LDR (experimental data from Whiteley, 1960)
4.2 Stamping of Complex Geometries – Predicting Optimal BHF Profiles with Adaptive Simulation

This work proposes a new algorithm to be implemented into the commercially available finite element method (FEM) code Pam-Stamp to predict optimal BHF spatial patterns and time profiles (adaptive simulation). At each time step, the algorithm attempts to maintain a quality parameter such as displacement, strain, stress, or force at a critical setpoint by actively varying the BHF using a general proportional integral derivative (PID) control scheme (see Figure 4.15). This strategy should produce an optimal BHF profile which maximizes quality characteristic such as final part strain while preventing such things as wrinkling and fracture. The procedure to compile routines into the code Pam-Stamp is included in Appendix C.

Table 4.1 summarizes the various control strategies that were investigated in this work. This table also summarizes the pros and cons of each strategy. Each strategy typically ensures the prevention of some type of part failure, while maximizing some part qualities and minimizing others. Depending on the functionality of the part, the designer should choose which strategy is most advantageous for him or her.

![Feedback algorithm for calculating optimal time and location variable BHF profiles using commercial FEM software - adaptive simulation](image)

Figure 4.15: Feedback algorithm for calculating optimal time and location variable BHF profiles using commercial FEM software - adaptive simulation
<table>
<thead>
<tr>
<th></th>
<th>Prevents</th>
<th>Maximizes</th>
<th>Minimizes</th>
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<tbody>
<tr>
<td>Binder Gap (Wrinkling)</td>
<td>Wrinkling</td>
<td>---</td>
<td>Part Strain Fracture</td>
</tr>
<tr>
<td>Punch Force</td>
<td>Fracture</td>
<td>Part Strain</td>
<td>Wrinkling</td>
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<tr>
<td>Max Thinning</td>
<td>Fracture</td>
<td>Part Strain</td>
<td>Wrinkling</td>
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<tr>
<td>Max Stress</td>
<td>Fracture</td>
<td>Part Strain</td>
<td>Wrinkling</td>
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</tbody>
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**Table 4.1: Summary of control strategies and their pros and cons**

### 4.2.1 Elasticity of the Blank Holder

Several issues arise in this development. First, how does the algorithm take into account the elasticity of the blank holder? This question addresses the coupling of the cylinders and will be discussed now.

The simplest assumption for the elasticity of the blank holder is to assume that the blank holder is segmented as shown in Figure 4.16. Although a segmented blank holder is typically not used in industry, the assumption of a segmented blank holder for modeling purposes is good when the blank holder is designed per Siegert’s (1998) serially-elastic rigid-cone design (see Figure 2.22). In Siegert’s design, the highly elastic connections between the highly rigid cones, ensures that the BHF cylinders will be largely uncoupled.

Thus, Siegert’s blank holder design acts very similarly to the segmented binder without the problems associated with multiple tool sections and possibility of damaging the sheet surface. Although the Siegert design is more complex, most automotive blank holders are sand casted and therefore geometric complexity does not significantly add manufacturing costs. The effect of BHF control is enhanced with Siegert’s design and computer modeling is made simpler.

A properly designed elastic blank holder can be assumed to be segmented in computer simulations if the coupling factor ($f_c$) is small (see Equation 2.9). A recommendation for
how small the coupling factor should be can be the subject of an investigation. If the coupling factor is large, then the BHF cylinders will not act independently and location variable BHF control will be hindered. To simulate such a case is possible, but to implement a feedback algorithm in order to control the process would present challenges. The coupling of the cylinders would reduce controllability of the process and may cause instability.

![Diagram](image)

Figure 4.16: Computer simulation model utilizing a segmented blank holder

### 4.2.2 Robustness of the Control Algorithm

Another issue that arises in this development is what values of the proportionality constants (k_p, k_i, and k_d) for the PID controller will satisfy the control requirements of this system? Also, what if two critical zones occur in the part at the same time? These issues deal with robustness of the control algorithm and will be addressed now.
In order to ensure that the control algorithm is robust and does not become unstable, it is vital to determine proper values of the three proportionality constants \( k_p, k_i, \) and \( k_d \). The control of a dynamic explicit FEM program was challenging. Even under good simulation conditions, the output force curves from an FEM program contain significant vibrations.

Further, the control algorithm must be robust enough to handle sudden shifts in the location of the critical zone. It is possible that two or more critical zones will be occur in a single part during the deformation process. The control algorithm must be able to absorb these sudden changes in the feedback parameters.

To do this, the fundamental methods of controls theory were be employed. Disturbances to the system was applied and the effects was observed. That is, the BHF was adjusted and its effect on the feedback parameters were examined as shown in Figure 4.17. The system response was obtained in this manner and with this information we calculated initial values for the control parameters with the equations below:

For a quarter decay ratio

\[
K_p = \frac{1.2}{R_{t_d}} \quad (\text{Equations 4.22}) \quad (\text{Ziegler, Nicols, 1942, 1943})
\]

\[
K_I = 2t_d
\]

\[
K_d = 0.5t_d
\]

\[
\frac{\sigma(s)}{BHF(s)} = \frac{Ke^{-\frac{t_d}{\tau}}}{\tau s + 1} \quad (\text{Equation 4.23}) \quad (\text{Ziegler, Nicols, 1942, 1943})
\]

Another method which proved useful, was to the set \( k_p, k_i, \) and \( k_d \) equal to zero and then increase \( k_p \) until steady state oscillation is observed in the response as shown in Figure 4.18. The period of oscillation (\( P_o \)) and the value of \( k_p \) at steady state oscillation (denoted \( k_u \)) is used to calculate the control parameters with the following equations:
\[ K_p = 0.6K_u \]
\[ K_i = 0.5P_u \]
\[ K_d = 0.125P_u \]

(Equations 4.24) (Callendar, 1936)

Figure 4.17: Step input function and typical response used to tune control systems

Figure 4.18: Steady state oscillation from proportional controller used to tune control systems

4.2.3 Wrinkling Based Adaptive Simulation

At each time step, this algorithm attempts to maintain the gap between the binder surfaces at a predetermined setpoint by actively varying the blank holder pressure (BHP) using a PID controller. This strategy should produce a BHF profile which ensures no wrinkling, minimizes final part strain and fracture. This algorithm allows the user to specify:

- \( k_p, k_i, k_d \) controller constants
- static and moving average filtering window sizes
- minimum and maximum BHF
- start time for control
- any linearly changing setpoint of binder gap for up to three different binder segments

The optimal values of $k_p$, $k_i$, $k_d$, and filtering parameters have been determined to maximize control robustness. These values are included in Appendix D. The minimum and maximum BHP levels should be set according to press and tool capacity. The start time should be set soon after deep drawing has begun typically after 2-3% of the draw depth has been achieved. It has been determined that the initial value of the binder gap setpoint should be 10% greater than the initial material thickness and the final value of the binder gap setpoint should be 10% greater than the final maximum thickness of the part. In general, a variation of binder gap setpoint from 1.1t to 1.5t, where t is the original material thickness, is sufficient. The binder gap strategy should produce a BHF profile which minimizes final part stretch while avoiding wrinkling.

Figure 4.19 shows an optimal BHP profile calculated from this algorithm for a 6” diameter round cup and a 12” diameter aluminum 6111-T4 blank. Notice that the binder gap vibrates around the setpoint. Similarly, the BHP varies throughout the process. At the end of the process, the binder position tends to vibrate with larger amplitude. Correspondingly, the BHP increases to counteract this phenomenon. No filtering or control settings could prevent this occurrence. It is believed that this is a numerical contact issue.

A 13” diameter aluminum 6111-T4 blank cannot be fully drawn under constant BHF conditions but was successfully drawn with this algorithm as shown in Figure 4.20. It can be seen that the thinning was reduced from 94% to 31% through this method. Figure 4.21 shows the predicted optimal BHP for a 5” by 12” by 15” rectangular pan and a 22.7” by 24.8” aluminum 6111-T4 blank (6.75” chamfer) with eight point binder control. Since
there are two planes of symmetry, only three channels of control are required. The
algorithm has been successfully expanded to up to three channels of control as shown.

Figure 4.19: Optimal predicted BHF time profile for 6" round cup and 12" aluminum
6111-T4 blank based on binder gap/wrinkling criterion

Figure 4.20: Thinning plot for constant and time variable BHF for a 6" round cup and
13" aluminum 6111-T4 blank after a 5.25" draw
Figure 4.21: Optimal time and location variable BHF profiles for a 5” by 12” by 15” rectangular pan and a 22.7” by 24.8” aluminum blank (6.75” chamfer) with eight point control based on binder gap/wrinkling criterion

4.2.4 Stress Based Adaptive Simulation

At each time step, this algorithm attempts to maintain the maximum equivalent stress in the part at some specified stress profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which maximizes the stretch in the part while eliminating fracture and minimizing wrinkling. The equivalent stress will be calculated from Hill’s plane stress anisotropic quadratic yield function (Wagoner, 1997).

$$
\bar{\sigma}^2 = \frac{1}{r_{90}(r_0 + 1)} \left[ r_{90} \sigma_x^2 + r_0 \sigma_y^2 + r_0 r_{90} (\sigma_x - \sigma_y)^2 + (2r_{45} + 1)(r_0 + r_{90}) \tau_{xy}^2 \right]
$$

(Equation 4.25)

This algorithm allows the user to specify:

- $k_p$, $k_i$, $k_d$ controller constants
- static average filtering window size
• minimum and maximum BHF
• start time for control or automatic start
• any constant level stress profile and ramp time
• bulk search of maximum stress or target zone or target element

The optimal controller and filtering constants have been iteratively determined to maximize robustness and are included in Appendix E. The maximum and minimum BHF are dictated by press and tooling limits. It is recommended that the initial BHF should be set relatively high near the fracture limit to minimize the amount of time it takes the stress reach the setpoint. The algorithm will quickly modify the BHF from this point on to ensure no splitting. This high initial BHF tends to improve control stability.

The start time should be set when the process is well established typically after 5-10% of the draw depth is achieved. There is also an option for the control to begin automatically when the measured stress becomes greater than or equal than the setpoint stress. This option improves control stability and is recommended as an initial starting point for investigations.

Any constant level stress profile may be specified and this setpoint can be ramped in at any slope to improve controllability. It is recommended that the stress setpoint be set at the average of the yield and ultimate tensile strength of the material to maximize stretch while avoiding splitting. The setpoint should be ramped in over a short period of about 5-10% of the draw depth.

The entire sheet or zone may be defined whereby the algorithm searches for the maximum stress. The zone option forces the algorithm to only analyze the region in which fracture is likely to occur to minimize false readings. Another option is to specify a specific element in which failure is likely to occur. It is recommended that a target element be chosen rather than the entire part or a zone to improve stability.
Figure 4.22 shows an optimal BHF profile predicted from this algorithm for the plane strain U-channel draw-bending of a 1” wide 6111-T4 aluminum blank. The stress tends to vary around the setpoint along with the BHF. The control strategy works very well with this simple geometry.

Figure 4.23 shows an optimal BHF profile predicted by the stress feedback algorithm for a 6” round cup and a 12” diameter 6111-T4 aluminum blank. The stress in the part varies wildly around the setpoint until the end of the process where the stress tends to zero. A stress profile from a fractured constant 40 mton BHF cup is included as reference. Comparing these two stress lines proves that the stress is being affected by the control algorithm. The optimal BHF profile from the simulation is shown on this graph along with an analytical predicted optimal BHF profile. Although the shapes and magnitudes of the curves are similar, the location of the minimum is time shifted.

![Optimal BHF Profile Predicted from Stress Algorithm](image)

Figure 4.22: Optimal BHF profile for plane strain U-channel draw bending of a 1” wide aluminum 6111-T4 blank based on stress criterion
Figure 4.23: Optimal BHF time profile for a 6” round cup and 12” aluminum 6111-T4 blank based on stress criterion

4.2.5 Strain Based Adaptive Simulation

At each time step, this algorithm attempts to maintain the maximum thinning in the part at some specified thinning profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which eliminates fracture in the part and minimizes wrinkling. The maximum thinning is defined as:

\[ \text{maximum thinning} = \frac{t_0 - t_{\text{min}}}{t_0} \]  

(Equation 4.26)

Where \( t_{\text{min}} \) is the minimum thickness in the part.

This algorithm allows the user to specify:

- \( k_p, k_i, k_d \) controller constants
- static average filtering window size
- minimum and maximum BHF
- start time for control
• any time rate of thinning

The optimal controller and filtering constants have been iteratively determined to maximize robustness and are included in Appendix F. The maximum and minimum BHF are dictated by press and tooling limits. The start time should be set soon after deep drawing has begun typically after 2-3% of the draw depth has been achieved. Any time rate of thinning may be specified. It is recommended that the thinning vary from 0% at the beginning of the process to around 30% by the end of the process to maximize stretch while avoiding splitting.

Figure 4.24 shows an optimal BHF profile predicted from this algorithm for a 6” round cup and a 12” diameter 6111-T4 aluminum blank. It is observed that the thinning follows the setpoint quite steadily. The optimal BHF variation tends to decrease throughout the stroke as expected. A thinning profile for a 40 mtons constant BHF round cup is included for reference purposes and indicates that the thinning was indeed controlled by this method.

Figure 4.24: Optimal BHF profile for 6” round cup and 12” aluminum 6111-T4 blank based on thinning criterion
4.2.6 Force Based Adaptive Simulation

At each time step, this algorithm attempts to maintain the punch force of the process at some specified force profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which eliminates fracture and minimizes wrinkling in the part. This algorithm allows the user to specify:

- $k_p$, $k_i$, $k_d$ controller constants
- static average filtering window size
- minimum and maximum BHF
- start time for control or automatic start
- any constant level force profile

The optimal controller and filtering constants have been iteratively determined to maximize robustness and are included in Appendix G. The maximum and minimum BHF are dictated by press and tooling limits. The initial value of the BHF should be set relatively high (near the fracture limit) in order to minimize the time it takes to reach the setpoint force. The controller will then modify the BHF to ensure that failure does not occur. Control stability is improved by setting the initial BHF high.

The start time should be set when the process is well established typically after 5-10% of the draw depth is achieved. There is also an option for the control to begin automatically when the measured punch force becomes greater than or equal than the setpoint force. This option improves control stability and is recommended as an initial starting point for investigations.

Any constant level of punch force may be specified. It is recommended that the punch force be set at 75% of the minimum punch force that causes fracture in constant level BHF trials. This should maximize final part stretch while avoiding splitting and minimizing wrinkling.
Figure 4.25 shows an optimal BHF profile predicted from this algorithm for a 6" round cup and a 12" diameter 6111-T4 aluminum blank. Once control begins, the punch force tends to vibrate around the setpoint. The optimal BHF profile tends to decrease then increase to maintain the punch load at the setpoint. An analytically predicted BHF profile is also shown in this figure. The shape and magnitude of the BHF profiles are similar in size and shape but are time shifted from one another.

Drawability is improved with the force algorithm as shown in Figure 4.26. A 13" diameter 6111-T4 aluminum blank cannot be fully drawn into a 6" round cup using constant BHF, but is successfully drawn with the force control strategy. Figure 4.27 shows an optimal BHF profile predicted for a 5” by 12” by 15” rectangular pan drawn from a 22.7” by 24.8” aluminum 6111-T4 blank (6.75” chamfer). The BHF profile vibrates wildly but can be smoothed with a filtering function for use in a press.

Figure 4.28 shows a thinning contour plot of this rectangular panel. Note that this maximum thinning is only 19%. The blank shape used for these rectangular simulations was predicted with the one-step FEM code FastForm3D to have a uniform flange after a 5” draw. This was proposed to maximize strain uniformity and increase drawability and part quality. It can be observed from this plot that the flange is relatively uniform. It is believed that the blank shape played major role in permitting a full 5” draw from aluminum.
Figure 4.25: Optimal BHF profile for 6” round cup deep drawing and 12” aluminum 611-T4 blank based on force criterion

Figure 4.26: Thinning plots for constant and variable BHF via force control strategy for a 6” round cup and 13” aluminum 6111-T4 blank after a 5.25” draw
Figure 4.27: Optimal BHF profile for a 5" by 12" by 15" rectangular pan and a 22.7" by 24.8" aluminum blank (6.75" chamfer) based on punch force feedback

Figure 4.28: Thinning contour plot for a 5" by 12" by 15" rectangular pan and a 22.7" by 24.8" aluminum blank (6.75" chamfer) based on punch force feedback
CHAPTER V

EXPERIMENTAL INVESTIGATION OF DEEP DRAWING AND STAMPING

5.1 Round Cup Deep Drawing

The objective of this investigation was to determine the drawability of various, high performance materials using a hemispherical, dome-bottomed, deep drawn cup (see Figure 5.1 and 3.2) and to investigate various empirical time variable blank holder force profiles. The materials that were investigated included AKDQ steel, high strength steel, bake hard steel, and aluminum 6111-T4 (see Table 5.1). Tensile tests were performed on these materials to determine flow stress and anisotropy characteristics for analysis and for input into the simulations (see Figure 5.2 and Table 5.2).

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
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<tbody>
<tr>
<td>AKDQ Steel</td>
<td>0.81</td>
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<tr>
<td>Aluminum 6111</td>
<td>1.20</td>
</tr>
<tr>
<td>High-Strength Steel</td>
<td>0.86</td>
</tr>
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</table>

Table 5.1: Materials used for the dome cup study

Figure 5.1: Dome cup tooling geometry (in millimeters)
It is interesting to note that the flow stress curves for bake hard steel and AKDQ steel were very similar except for a 5% reduction in elongation for bake hard. Although, the elongations for high strength steel and aluminum 6111-T4 were similar, the n-value for aluminum 6111-T4 was twice as large. Also, the r-values for AKDQ was much bigger than 1, while bake hard was nearly 1, and aluminum 6111-T4 was much less than 1.

The time variable BHF profiles used in this investigation included constant, linearly decreasing, and pulsating (see Figure 5.3). The experimental conditions for AKDQ steel were simulated using the incremental FEM code Pam-Stamp. Examples of wrinkled, fractured, and good laboratory cups are shown in Figures 2.14 and 2.15 as well as an image of a simulated wrinkled cup.

Limits of drawability were experimentally investigated using constant BHF. The results of this study are shown in Table 5.3. This table indicates that AKDQ had the largest drawability window while aluminum had the smallest and bake hard and high strength steels were average. The strain distributions for constant, ramp, and pulsating BHF are compared experimentally in Figure 5.4 and are compared with simulations in Figure 5.5 for AKDQ. In both simulations and experiments, it was found that the ramp BHF trajectory improved the strain distribution the best. Not only were peak strains reduced by up to 5% thereby reducing the possibility of fracture, but low strain regions were increased. This improvement in strain distribution can increase product stiffness and strength, decrease springback and residual stresses, increase product quality and process robustness.

Pulsating BHF, at the frequency range investigated, was not found to have an effect on strain distribution. This was likely due to the fact the frequency of pulsation that was tested was only 1 Hertz. It is known from previous experiments of other researchers that proper frequencies range from 5 to 25 Hertz (Siegert, 1995). A comparison of load-stroke curves from simulation and experiments are shown in Figure 5.6 for AKDQ.
Good agreement was found for the case where $\mu=0.08$. This indicates that FEM simulations can be used to assess the formability improvements that can be obtained by using BHF control techniques.

<table>
<thead>
<tr>
<th>Aluminum 6111-T4 (0.040&quot;)</th>
<th>AKDQ Steel (0.032&quot;)</th>
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</thead>
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<tr>
<td>E (GPa)</td>
<td>K (MPa)</td>
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<tr>
<td>0°</td>
<td>64</td>
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<tr>
<td>45°</td>
<td>64</td>
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<td>Average</td>
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<td>Range</td>
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</table>

<table>
<thead>
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<th>Bake Hard Steel (0.032&quot;)</th>
<th>High Strength Steel (0.034&quot;)</th>
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<td>K (MPa)</td>
</tr>
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<td>Average</td>
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<td>Range</td>
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</tr>
</tbody>
</table>

Table 5.2: Tensile test data for aluminum 6111-T4, AKDQ, high strength, and bake hard steels

Figure 5.2: Results of tensile tests of aluminum 6111-T4, AKDQ, high strength, and bake hard steels

a) Fractured tensile specimens

b) Flow stress curves for various materials
Figure 5.3: BHF time-profiles used for the dome cup study

<table>
<thead>
<tr>
<th>Material</th>
<th>Wrinkling Limit</th>
<th>Best</th>
<th>Fracture Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
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<td>70 kN</td>
<td>90 kN</td>
</tr>
<tr>
<td>AKDQ</td>
<td>60 kN</td>
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</tr>
<tr>
<td>High Strength Steel</td>
<td>70 kN</td>
<td>150 kN</td>
<td>250 kN</td>
</tr>
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</table>

Table 5.3: Limits of drawability for dome cup with constant BHF
Figure 5.4: Experimental effect of time variable BHF on engineering strain in an AKDQ steel dome cup

Figure 5.5: Simulated effect of time variable BHF on true strain in an AKDQ steel dome cup
Figure 5.6: Comparison of experimental and simulated load-stroke curves for an AKDQ steel dome cup

5.2 Rectangular Pan Deep Drawing
In order to investigate BHF control, a rectangular cavity tooling was designed at the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) in Columbus, Ohio. A schematic of the design is shown in Figure 3.5, and a solid model is shown in Figure 3.3. The tooling has multiple punches including flat, singly curved, and two leveled (oil pan). The binder includes four locations for insertable drawbeads of three different heights.

Laboratory experiments were conducted with the rectangular tooling and the flat punch to investigate BHF control. A 160 ton hydraulic Minster press was used to impart the forming force and eight nitrogen cylinders were used to impart the BHF. The process parameters are shown in Table 5.4. The material and blank geometries are shown in Figure 5.7. Two spatial BHF patterns were studied: uniform and nonuniform. These patterns are shown in Figure 5.8. Essentially, the uniform BHF pattern consists of each
nitrogen cylinder imparting 5.2 tons (41.6 tons total). The nonuniform pattern consists of the corner cylinders set to 4.4 tons each and the side cylinders set to 6.0 tons each.

The reasoning behind the nonuniform BHF pattern has to do with the material flow pattern shown in Figure 2.26. Typically the corners do not draw in and fracture occurs in the wall near the corners. The sides tend to draw greatly which may cause shape problems or even structural integrity problems such as oil canning (elastic instability). Thus, the nonuniform pattern reduces the BHP in the corners to increase drawability and increases the BHP in the sides to improve part quality. The results of the experiments are shown in Figure 5.9. These pictures show each material and blank geometry drawn under both BHF patterns. Fracture depths were increased up to 25% using this BHF control technique without any reduction of part quality. Wrinkling measurements were used to estimate part quality.

A finite element method (FEM) model of the rectangular tool was developed to investigate BHF control. In this model, the punch and die were discretized with rigid shell elements and the sheet was meshed with elastic-plastic shells. The blank holder was meshed with elastic brick elements so that the effects of nonuniform BHF patterns could be included. The meshed FEM model is shown in Figure 2.38. In Figure 5.10, the pressure patterns caused by the contact between the nitrogen cylinders and blank holder can be seen for both BHF patterns. This model can be used to find the optimal spatial BHF patterns and time trajectories.

Comparisons were made between experiments and simulations. Figure 5.11 shows comparisons between punch force measurements and predictions. A coefficient of friction of 0.075 was shown to give the best comparison (5% maximum error). Figure 5.12 shows strain comparisons made along the diagonal section shown. Good agreement was found for the same coefficient of friction (5% maximum error).
| Two Blank Holder Force Patterns | 1. Uniform BHF pattern (41.6 tons)  
2. Nonuniform BHF pattern (41.6 tons) |
|---------------------------------|------------------------------------------------|
| Four Blank Types                | 1. Rectangular Aluminum (0.040"x20"x23")  
2. Oval Aluminum (0.040"x19.25"x22.25")  
3. Rectangular AKDQ steel (0.030"x20"x23")  
4. Chamfered AKDQ steel (0.030"x20"x23" with 2.25" chamfer) |
| Two Draw Depths                 | 1. 2” Draw (50.8 mm)  
2. 3.5” Draw (88.9 mm) |
| Punch Speed                     | 3.5 in/s (90 mm/s) |

Table 5.4: Process parameters for rectangular pan experiments

![Blank shapes used in the rectangular pan study](image)

Figure 5.7: Blank shapes used in the rectangular pan study

![Experimental BHF patterns for the rectangular pan studies](image)

Figure 5.8: Experimental BHF patterns for the rectangular pan studies
Figure 5.9: Effect of location variable BHF control on rectangular pan drawing
Figure 5.10: Simulated BHF patterns for the rectangular pan study (see Figure 5.8)

Figure 5.11: Predicted and measured punch force comparisons for 2008-T4 aluminum rectangular pan
5.3 Asymmetric Panel Stamping

The material that was investigated was AKDQ (aluminum killed draw quality) steel. Its material properties are listed below in Table 5.5. A chamfered blank shape was used in the experiments as shown in Figure 5.13. Eight blanks were prepared for each emboss geometry for a total of 24 blanks. Two blanks were circle gridded for each emboss geometry for strain measurements.

Screening experiments were performed to determine the process limits on such parameters as blank holder force, binder gap, pad force, and lubrication. Once the screening was complete, sensitivity experiments were conducted for each emboss geometry. The BHF, binder gap, pad force, and lubrication was varied and each part was examined for all possible failures including splitting, wrinkling, and rabbit earing. The slide tonnage was recorded for each part as well.

Table 5.6 shows the results obtained from the experiments. Optimal conditions for forming were determine to be at 50 tons of BHF, zero thickness binder gap, full oil-based
water soluble lubrication, and 1250 psi pad pressure. Fracture was observed to occur at 75 and 100 tons of BHF and at fast press speeds (3.54 inches/second). Wrinkling was observed to occur at 25 tons BHF and at binder gaps equal to one and two times the blank thickness. Rabbit earing was not observed to occur on any of the panels at any process condition. Pad pressure was applied to the panel but did not have an observable effect on the panel quality nor did it have a measurable effect on the strain distribution.

Figure 5.14 contains sample pictures of the asymmetric panel with the oval door emboss. Similarly, Figure 5.15 shows sample pictures for the rectangular emboss and Figure 5.16 for the oblong emboss. In order to observe the history of deformation, a binder wrap panel was formed as shown in Figure 5.17. A panel was formed one inch off bottom as well and is shown in Figure 5.18. The history of deformation appeared to be good since no gathering of material was observed.

Figure 5.19 indicates the locations and directions of strain measurements for each of the asymmetric panels. Figure 5.20 is a graph of the major strain distribution versus original blank position. This graph is indicated with positions A, B, C, and D which correspond to the lettered positions in Figure 5.19. Essentially, A is located at the near panel wall (header/sweeping curvature), B is at the beginning of the emboss, C is at the far edge of the emboss and D is at the far panel wall (width side). It is observed that the oval emboss distributes the strain the best while the oblong emboss distributes the strains the worst.

The initial design was confirmed using Pam-Stamp simulations. The model is shown in Figure 5.21. It is important for the strain in the panel to exceed 3% so that springback does not greatly effect final part geometry. The simulations showed that the asymmetric part strain mostly exceeded the 3% minimum. Several attempts were made to maximize this area including increasing the punch radius and increasing the blank holder force. These methods helped but not significantly. Increasing the blank holder force does increase the strain but it also increases the likelihood of fracture. Figure 5.22 is a strain
distribution of the simulated panel. The majority of the pan is well above the 2% range, as shown in Figure 5.23 providing springback resistance. The predicted strain distribution is noted to be of similar magnitude and distribution as the experiment observations.

Pam-Stamp simulations were performed on each of the embossing geometries. Defects appeared around the door handle indentation in each panel. The oval emboss is shown in Figure 5.24. The figure shows the velocity contour for the vertical direction. The material has a greater amount of movement locally on either side of the door handle formation. This indicates that the material was buckling at these locations. A section cut of the displacement confirms this result. Figure 5.25 shows the location of the cut and Figure 5.26 is the graph of the vertical displacement. The section cut is compared to the punch curvature to illuminate the defect. The large defect appears to be approximately 25 mm in height and 50 mm wide along the cut. It is difficult to detect this defect with a displacement contour such as in Figure 5.25, due to the small amplitude. However, deflections this small can be detected once a panel has been painted.

The second geometry is shown in Figure 5.27. This geometry is harder to form due the tight corners and the shallow depth. The corners indicated by (1) have a single protrusion near the corners. Item (2) points to where the material has formed a “pie crust” around the corner. The third area is a deformation that occurs along the bottom side and the right side of the punch. Item (3) is a long bulge in the vertical direction directly next to the embossing. The sides close to the punch curvature withstand a higher amount of tension compared to these sides. A detailed sketch of the deformation is given in Figure 5.28. In addition, section cuts were performed next to each corner. Two of the section cuts are shown in Figures 5.29 and 5.30.
The conclusions of this investigation are:

- Experiments were conducted using the asymmetric tooling and AKDQ steel for three types of emboss geometries.
- Process limits, strain distributions, and panel quality was recorded.
- The oval emboss provide the highest quality part surface.
- Simulation were successfully conducted to predict rabbit earing.
- Simulation results were reasonable when compared to experimental observations.
- Different materials such as aluminum, high strength steel, bake hard steel should be investigated.
- Different emboss geometries should be investigated.

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<th>Material Type</th>
<th>Young Modulus (GPa)</th>
<th>Poisson Ratio</th>
<th>Yield Stress (MPa)</th>
<th>K-value (MPa)</th>
<th>n Value</th>
<th>r Value</th>
<th>Prestrain ε₀</th>
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</thead>
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<td>536.5</td>
<td>0.227</td>
<td>1.62</td>
<td>0.0044</td>
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</table>

Table 5.5: AKDQ steel material properties

Figure 5.13: Chamfered blank shape for the asymmetric panel (in millimeters)
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<tr>
<th>Part #</th>
<th>Door Handle Type</th>
<th>Binder Gap</th>
<th>BHF Setting (mtons)</th>
<th>Blank Thick (inch)</th>
<th>Press Speed</th>
<th>Slide Force (mtons)</th>
<th>Cushion Force (mtons)</th>
<th>Pad Pressure (psi)</th>
<th>Part Quality</th>
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<td>100</td>
<td>0.0320</td>
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</tbody>
</table>

Table 5.6: Results of asymmetric panel experiments
* indicates gridded parts
Figure 5.14: Oval embossed asymmetric panel

Figure 5.15: Rectangular embossed asymmetric panel
Figure 5.16: Oblong embossed asymmetric panel

Figure 5.17: Binder wrap asymmetric panel

Figure 5.18: Asymmetric panel formed 1" off bottom
Figure 5.19: Gridded parts and measurement point locations for the asymmetric panel
Figure 5.20: Experimental strain distribution for the asymmetric panel

Figure 5.21: Computer simulation model of the asymmetric tooling
Figure 5.22: Major strain contour plot of the asymmetric panel

Figure 5.23: Major strain versus curvilinear distance for the asymmetric panel

Note: The line on the panel above denotes the section along which the strain data was taken for the graph. The letters in the graph represent the positions shown on the panel.
Figure 5.24: Velocity contour of oval embossed asymmetric panel

Figure 5.25: Z-displacement contour of oval embossed asymmetric panel
Figure 5.26: Cross sectional cut of asymmetric panel shown in Figure 5.25

Figure 5.27: Rectangular embossed asymmetric panel showing defects around the emboss
Figure 5.28: Local defects around the rectangular embossed asymmetric panel

Figure 5.29: Cross section of rectangular embossed asymmetric panel at lower left corner

Figure 5.30: Cross section of rectangular emboss asymmetric panel at lower right corner
CHAPTER VI

PART, DIE, AND PROCESS DESIGN METHODOLOGY
FOR DEEP DRAWING AND STAMPING

6.1 Near Zero Stamping

In 1994, the Auto Body Consortium (ABC) submitted the proposal entitled Near Zero Stamping (NZS) to the National Institute of Science and Technology's (NIST) Motor Vehicles Manufacturing Advanced Technology Program. In the NZS project, 26 automotive companies provided matching funds along with NIST funding to achieve a total project budget of $18 million for 4 years. Five research institutions were chosen to conduct the technical work of the project which included the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) at the Ohio State University.

The author of this dissertation has managed this project as a full time engineer for the ERC/NSM since kick off. Part of the intent of this work is to deliver this dissertation and its contributions as part of the Near Zero Stamping project and to the members of the Auto Body Consortium.

The Near Zero project was organized into four projects and eleven tasks of which the ERC/NSM was involved in three tasks. This dissertation will largely concentrate on two of these tasks whose primary goals are respectively:

- Task 1.2: Computer Simulation - To develop a methodology to implement computer simulation into the auto body design process and to produce the necessary technologies to make this possible/easier.
• Task 1.3: Sensitivity Analysis - To generate sensitivity data (input/output relationships) of the basic, fundamental part geometries and processes involved in sheet metal forming and to organize this data in a usable and easy to access format for design engineers.

6.1.1 The Concept to Production Process

The design process of complex shaped sheet metal stampings such as automotive panels, consists of many stages of decision making and is a very expensive and time consuming process. Currently in industry, many engineering decisions are made based on the knowledge of experienced personnel and these decisions are typically validated during the soft tooling and prototyping stage and during hard die tryouts as shown in Figure 6.1a. Very often the soft and hard tools must be reworked or even redesigned and remanufactured to provide parts with acceptable levels of quality.

The best case scenario would consist of the process outlined in Figure 6.1b. In this figure, the part design phase does not end after computer aided design. The initial product design is immediately simulated on the computer to estimate formability and a feedback loop is introduced in case redesign is required. This would allow the product designer to make necessary changes up front as opposed to down the line after expensive tooling has been manufactured.

One-step FEM is particularly suited for product analysis since it does not require binder, addendum, or even most process conditions. Typically this information is not available during the product design phase. One-step FEM is also easy to use and computationally fast, which allows the designer to play “what if” without much time investment. Without the use of FEM simulation during the part design phase, the die and process design phase may be fraught with the task of developing a good process from a bad part design. This proposed design methodology will lead to reductions in costs and lead times for these reasons.
Once the product has been designed and validated, the development project would enter the time zero phase and would be passed onto the die designer. The die designer would validate his/her design with an incremental FEM code and make necessary design changes and perhaps even optimize the process parameters to ensure not just minimum acceptability of part quality, but maximum achievable quality. This increases product quality but also increases process robustness. Incremental FEM is particularly suited for die design analysis since it does require binder, addendum, and process conditions which are either known during die design or desired to be known.

The most common use of FEM simulation in industry is to estimate the formability of the process and to determine the most optimal process conditions. The elimination of splitting and wrinkling via BHF and drawbeads is not the only possible use. The prediction of gravity/binder wrap conditions, impact line movement, surface distortions, trimming/piercing, springback, ideal blank shape, and optimum BHF trajectory/pattern may also be achieved. A proposed simulation methodology will be presented in the next subsection for the design of complex stampings which fully utilizes the potential of computer simulation.

The validated die design would then be manufactured directly into the hard production tooling and be validated with physical tryouts during which the prototype parts would be made. Tryout time should be decreased due to the earlier numerical validations. Redesign and remanufacturing of the tooling due to unforeseen forming problems should be a thing of the past. The decrease in tryout time and elimination of redesign/remanufacturing should more than make up for the time used to numerically validate the part, die, and process.

In Figure 6.1, notice that the experience of the engineer is not replaced with computerized tools. On the contrary, the experience of the engineer is an integral part of this process. If the experience of an engineer is limited for whatever reason, then the educational
modules provided by this research may bring the engineer up to speed. Further, this research will provide a computerized database which will provide the effect of process parameters on product quality. This sensitivity database can be used as a reference along with the experience of the engineer.

![Diagram of Current and Proposed Design Methodology]

Figure 6.1: Current and proposed design methodology for sheet metal stampings

6.1.2 Final Deliverables to NZS

A stamping design methodology has been developed and programmed into an interactive module. The vision of this module is to provide the user with an interface into each and every deliverable of the NZS project including reports, presentations, modules, databases, cases studies, beta tests, and analysis programs. This final deliverable will document the methodology to utilize these newly developed technologies into the current stamping design process.
The concept will be to outline the auto body design process using flowcharting techniques and provide this user with a clickable exploding map of the process as shown in Figures 6.2 through 6.4. On each page, clickable items may lead the user deeper into the module or to related deliverables. In this way, a user who is searching for help may find the information and tools in an environment which is familiar to them.

The highest level of final deliverable is shown in Figure 6.2. Here the auto body realization methodology is outlined from concept to production. By clicking on the “Part Design” box, the user is transported into the page shown in Figure 6.3, which outlines the stamping part design methodology. If the user clicks on the “Die Build” box in Figure 6.2, he or she is taken to the page shown in Figure 6.4, which is the stamping die build methodology. Please note that on each of these pages are clickable items which take the user directly to related deliverables.

For example if the user is trying to solve a splitting problem, then he or she may click into the "Stamping Die Build" section, then click "Splitting". The user will then find pictures of split parts and methods to predict splitting including forming limit diagrams and failure criteria. A list of possible solutions to splitting problems will be included such as:

- Decrease BHF, drawbead restraint, and blank size.
- Increase lubrication, material thickness, material grade, n-value, $\bar{\sigma}$-value, and part/die radii.
- Modify blank shape/location, binder and addendum geometry.

Each of the above solutions would be clickable to allow the user to understand how to implement each of these. Furthermore, the user would have access to any reports, case studies, databases, modules, and software that would contain useful information on splitting. In this case the list of tools would be:

• Door Outer Case Study
• Experience/Sensitivity Database
• Deep Drawing Interactive Module
• Sheet Forming Design System Spreadsheet
• Sectionform - 2D FEM Analysis
• Adaptive Simulation - Optimal BHF Profiles

Thus, the user begins with a problem, then he or she peruses the design methodology module through a series of choices and hyperlinks. Then the user is provided with useful information and access to appropriate tools. In this way, the user is presented a methodical solution and the means to implement this solution.

Figure 6.2: Auto body realization methodology
Figure 6.3: Stamped part design methodology

Figure 6.4: Stamping die build methodology
6.1.3 Reports, Case Studies, Databases, Modules, and Software

A complete list of reports, cases studies, databases, modules, and software that will be delivered to the members of Near Zero Stamping are included in Appendix H. A summary list is included in Table 6.1 below.

<table>
<thead>
<tr>
<th>REPORTS</th>
<th>MULTI-MEDIA MODULES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1.2 Simulation Reports (8)</td>
<td>Bend Module</td>
</tr>
<tr>
<td>Task 1.3 Sensitivity Reports (8)</td>
<td>Deep Draw Module</td>
</tr>
<tr>
<td>Task 1.4 Hemming Reports (7)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PROGRAMS</th>
<th>FUNDAMENTAL MODULES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend, Flange Program</td>
<td>Sheet Forming as a System</td>
</tr>
<tr>
<td>Drawbead Force/Geometry Calculator</td>
<td>Bending, Flanging, Hemming</td>
</tr>
<tr>
<td>BHF Profile Calculator</td>
<td>Part &amp; Process Design for Stamping</td>
</tr>
<tr>
<td>Sheet Forming Design System</td>
<td>Product Quality</td>
</tr>
<tr>
<td>SectionForm 2D FEM</td>
<td>Recent Technologies</td>
</tr>
<tr>
<td>Adaptive Simulation</td>
<td>Industrial Case Studies</td>
</tr>
<tr>
<td></td>
<td>Management Issues</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DATABASES</th>
<th>INDUSTRIAL CASE STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experience/Sensitivity Database</td>
<td>LHS and Caravan Door Outer</td>
</tr>
<tr>
<td>Hemming Database</td>
<td>Honda Wheel House</td>
</tr>
<tr>
<td>Glossary of Terminology</td>
<td>Deck Lid Outer</td>
</tr>
<tr>
<td>Publications Database</td>
<td>Roof Panel</td>
</tr>
<tr>
<td></td>
<td>Fender Outer</td>
</tr>
<tr>
<td></td>
<td>Cabin Inner</td>
</tr>
<tr>
<td></td>
<td>Instrument Panel</td>
</tr>
<tr>
<td></td>
<td>Truck Door - Hemming</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INDUSTRIAL BETA TESTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab Corner DOE Investigation</td>
<td></td>
</tr>
<tr>
<td>GM Wheel House Beta Test</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1: List of Near Zero Stamping deliverables
6.2 Industrial Case Studies

6.2.1 Deck Lid Soft Tool Tryouts - Case Study

This section will discuss the results of a deck lid simulation. Two materials were simulated and formed in physical soft tool tryouts, 1004 AKDQ steel and 6111-T4 aluminum. The material properties are listed in Table 6.2. The process conditions used in the simulations are listed in Table 6.3. The panel geometry was symmetrical, so only half of the tooling was simulated.

The geometry for a rear deck lid draw die was obtained in IGES format and imported into I-DEAS, so that it could be cleaned and meshed. A coarse mesh was initially defined, so that adaptive mesh refinement could later be used in regions of sharp geometry. The meshed surfaces of the die, binder, sheet, and trim line were imported into Pam-Stamp’s preprocessor module. The punch surface was created by offsetting the die surface by a sheet thickness. The opposing binder surface was similarly created.

The first step in the forming process was binder wrap. This was simulated by orienting the sheet between the binder surfaces and closing the binders together using a velocity boundary condition. This process formed the initial blank shape shown in Figure 6.5a into the binder wrap sheet shape shown in Figure 6.5b. The second step was to simulate the stretch-draw operation. The appropriate binder force was applied and the punch was assigned a velocity boundary condition. A typical drawbead restraining force was then applied and the result is shown in Figure 6.6 for both materials. Severe wrinkling occurred in the product area for the aluminum blank due to loose material in the die. The steel blank does not exhibit the severe wrinkling but still exhibits less than 1% strain in the same region indicating a similar loose material condition. These predictions were also observed during the soft tool tryouts. The loose material issue was resolved using a drawbar in the addendum region as shown in Figure 6.7.
The maximum thinning and thickening in both materials are indicted in Table 6.4. These numbers show aluminum’s tendency to thin and thicken more than steel in this process presumably due to lower normal anisotropy values which increases the tendency to strain in the thickness direction. Both materials exhibit thinning in excess of 24% indicating potential failure. The maximum thinning area occurred in the license plate depression as shown in Figure 6.8. The drawbead restraining force in this area was reduced to feed material into this high strain region. Eighty millimeters of material flow was required to relieve this splitting condition as predicted by the simulation. During soft tool tryouts, 70mm of metal flow was required indicating good correlation between predictions and observations.

Pam-Stamp was then used to trim the excess material from the flange. The springback was then calculated and a contour plot of the springback displacement is shown in Figure 6.9. The maximum springback was predicted to be 3.7mm inboard along the edge below the license plate depressions. The soft tool tryouts indicated that the location was correct and that the deflection was 4.5mm, again confirming predictions. Once the process was optimized, the predicted drawbead restraining forces were used to predict drawbead geometry using analytical equations as shown in Figure 6.10.

<table>
<thead>
<tr>
<th>Blank Holder Force</th>
<th>110 tons (100 metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Model</td>
<td>Coulomb Friction (μ = 0.1)</td>
</tr>
<tr>
<td>Forming Depth</td>
<td>5.9” (150 mm)</td>
</tr>
<tr>
<td>Punch Velocity</td>
<td>15 mm/ms</td>
</tr>
</tbody>
</table>

Table 6.2: Process conditions for the deck lid simulations
<table>
<thead>
<tr>
<th></th>
<th>1004 AKDQ Steel</th>
<th>6111-T4 Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus</td>
<td>200 GPa</td>
<td>70 GPa</td>
</tr>
<tr>
<td></td>
<td>(29.0 x $10^6$ psi)</td>
<td>(10.2 x $10^6$ psi)</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.300</td>
<td>0.300</td>
</tr>
<tr>
<td>Strength Coefficient</td>
<td>0.5365 GPa</td>
<td>0.533 GPa</td>
</tr>
<tr>
<td></td>
<td>(77812 psi)</td>
<td>(77302 psi)</td>
</tr>
<tr>
<td>Strain Hardening Exponent</td>
<td>0.227</td>
<td>0.238</td>
</tr>
<tr>
<td>Prestrain</td>
<td>0.00442</td>
<td>0.0010</td>
</tr>
<tr>
<td>Normal Anisotropy</td>
<td>1.62</td>
<td>0.59</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.75 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td></td>
<td>(0.030&quot;)</td>
<td>(0.039&quot;)</td>
</tr>
</tbody>
</table>

Table 6.3: AKDQ steel and aluminum 6111-T4 material properties

Figure 6.5: Blank and binder wrap sheet shapes for the deck lid
Figure 6.6: Prediction of wrinkling and loose material in the deck lid

Figure 6.7: Using a drawbar to eliminate loose material
<table>
<thead>
<tr>
<th></th>
<th>Thinning</th>
<th>Thickening</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKDQ Steel</td>
<td>24%</td>
<td>7%</td>
</tr>
<tr>
<td>6111-T4 Aluminum</td>
<td>27%</td>
<td>13%</td>
</tr>
</tbody>
</table>

Table 6.4: Thinning and thickening for aluminum 6111-T4 and AKDQ steel deck lids

Figure 6.8: Prediction of splitting and material flow in the deck lid

Figure 6.9: Prediction of trimming and springback in the deck lid
Figure 6.10: Prediction of drawbead geometry for the deck lid

### 6.2.2 Fender Outer Hard Die Tryouts - Case Study

The PL fender hard die tryout simulations were initiated simultaneously with the physical hard die tryouts at a die manufacturer. The FEM model is shown in Figures 6.11 and 6.12 and the process parameters are listed in Table 6.5. Preliminary simulations were conducted before the exact process settings were known. Although these simulations seem premature, they helped to developed a knowledge base.

The initial simulation assumed lockbead conditions and is shown in Figure 6.13. Splitting was noticed along the wheel well area. The first hit during the actual tryouts split in the same region. We believe that improper balancing may have caused excessive binder force in this region causing the material to lock instead of draw.

The secondary simulations assumed a drawbead condition and is shown in Figure 6.14. Possible shape distortion, splitting in three distinct regions, and a lack of material was predicted. The fifth hit during the actual tryouts showed splitting and a lack of material in the same regions thus validating the predictions.
We received the exact draw bead geometry and blank holder force and incorporated the new information into the third set of simulations. Figure 6.15 shows the binder wrap and shaded images of the deformation history of the fender. Figure 6.16 shows the draw-in pattern after the draw stage which predicts a lack of material in the wheel well region. Figure 6.17 shows a strain contour which predicts areas of low strain.

The combination of poor binder wrap, excessive material flow, and insufficient length of line caused the low strain problem in the simulation. After trimming the tryout fender, the region of low strain could not retain its geometry thus validating the predictions. Gainers were added to the section between the left and right hand fenders as shown in Figure 6.18 to eliminate the low strain condition.

Final process conditions were provided by the die manufacturer for the final fender simulations. The blank, drawbeads, BHF, and balancing blocks were redesigned as shown in Figure 6.19. The changes were implemented into the simulation, and final simulation was run. Figure 6.20 shows that a good panel was obtained thus ending the tryouts.

The simulated panel was trimmed as a final exercise and is shown in Figure 6.21. To aid in the visualization of the simulated fender geometry, rapid prototypes were made of the binder wrap, 75% draw, and 100% draw (Figure 6.22). Nodal and connectivity data were obtained from Pam-Stamp and fed into a custom-made software developed by the ERC/NSM to generate stereolithography (STL) files. The STLs were then downloaded into a fused deposition machine (FDM) to create the models. This process is referred to as virtual processing.
<table>
<thead>
<tr>
<th>BHF: 548 kN, 768 kN</th>
<th>Stress/Strain: $\sigma=550\left[\varepsilon+0.0049\right]^{0.208}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawbead: Locked, 100 N/mm, 139 N/mm</td>
<td>Anisotropy: $r_{ave}=1.70$</td>
</tr>
<tr>
<td>Part Depth: 134.0mm</td>
<td>Tool Friction ($\mu$): 0.10 all tools</td>
</tr>
<tr>
<td>Material: AKDQ Steel</td>
<td>Drawbead Friction ($\mu$): 0.17 on drawbeads</td>
</tr>
<tr>
<td>Thickness: 0.7112mm thick</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.5: Process parameters for the fender outer simulations

**Figure 6.11:** Finite element model of the fender

**Figure 6.12:** Blank and drawbead layout for the fender
a) Shaded image of material draw-in

b) Thinning contour

c) Tryout panel

Figure 6.13: Initial fender simulation results and comparisons with tryout (lockbead ~ BHF: 548 kN)
Figure 6.14: Secondary fender simulation results and comparisons with tryout (drawbead: 100 N/mm ~ BHF: 548 kN)
Figure 6.15: Tertiary fender simulation results - deformation history (drawbead: 139 N/mm ~ BHF: 786 kN)

Figure 6.16: Tertiary fender simulation results - material draw-in (drawbead: 139 N/mm ~ BHF: 786 kN)
Figure 6.17: Tertiary fender simulation results - low strain regions (drawbead: 139 N/mm ~ BHF: 786 kN)
Figure 6.18: Eliminating low strain through the use of gainers

Figure 6.19: New process conditions for the fender

Blank Holder Force: 103.7 tons

Friction Coefficient:
\[ \mu = 0.10 \text{ for tooling} \]
\[ \mu = 0.17 \text{ for beads} \]
BHF applied with balancing blocks
Semi-circular DBF: 69.5 N/mm
Rectangular DBF: 283.4 N/mm

Figure 6.20: Final simulation results for the fender

Figure 6.21: Trimmed fender results
Figure 6.22: Rapid prototype of fender simulation - virtual processing
CHAPTER VII

CONCLUSIONS AND FUTURE WORK

7.1 Summary
This dissertation has provided the results of a literature search on deep drawing, stamping, and blank holder force control in Chapters 1 and 2. This literature review made it clear that more advanced tools were needed to help engineers design better parts and processes. In particular, a method to predict optimal BHF profiles was lacking. Furthermore, a design methodology that properly outlined the use of these tools in the current part design process was needed.

A detailed research plan was provided in Chapter 3 that would develop and validate this proposed design methodology and tools. Two methods were presented in Chapter 4 to predict optimal BHF profiles: analytical equations and FEM with feedback (adaptive simulation). The purpose of the analytical equations was to allow an engineer to quickly obtain optimal BHF profiles for simple parts. The adaptive simulation method will be useful for predicting BHF profiles for complex stampings. Also, a method to predict splitting in stamping was analytically derived. The procedures and derivations were accounted for in detail in Chapter 4.

In Chapter 5, the results of an experimental study of the deep drawing and stamping process was provided. These experiments were used to validate the analytical and numerical models developed in Chapter 4. Comparisons were made between predictions of optimal BHF profiles and observations. In general, agreement was good indicating that the proposed approach is valid.
A general description for the proposed design methodology was provided in Chapter 6. This system outlines the current and proposed design methodology. The proposed design methodology designates when in the design process does each tool or module enter in. This design methodology provides the framework by which engineers may improve their stamping designs. The analytical and empirical tools of this research will allow engineers to conduct their work more scientifically. The educational modules provided by this dissertation will deliver these concepts and tools to engineers in an efficient manner. In addition, the results and deliverables of the Near Zero Stamping project was described.

7.2 Research Results

The following research contributions to the state of the art were developed through this dissertation:

- Part and process design methodology for the deep drawing and stamping of sheet metal parts that will lead to a robust process with improved drawability.
- Computerized tools that provide engineers with the effect of process parameters on part quality (sensitivity data) for various simple tool geometries from laboratory experiments and computer simulations.
- Mathematical model and computer software that allows engineers to calculate forming forces, formability limits, required tool geometry, and optimal BHF profiles for simple part geometries such as round cups, rectangular pans, U-channels, hemispherical shells, and asymmetric panels.
- Module for commercial finite element method (FEM) programs that implements a feedback loop into the calculations (adaptive simulation) in order to determine optimal process BHF time profiles and spatial patterns for general complex geometries.
7.3 Conclusions

The following conclusions are made based on the previously described dissertation work:

- Three new laboratory tools have been designed, built, and implemented through this dissertation work including the rectangular pan tooling, the hydraulic BHF control system, and the asymmetric panel tooling.
- The analytical and numerical models were successfully validated through the use of laboratory experiments on round, rectangular, and asymmetric parts.
- The analytical and numerical models successfully predict optimal time and location variable BHF profiles for simple deep drawing and complex stamping.
- The proposed design methodology has been validated through a series of industrial cases studies.
- A variety of tools has been developed for the sheet forming engineer including an interactive module which guides the user through the proposed design methodology and provides him or her with access to reports, cases studies, databases, modules, and software developed through the NZS project.
- The results of this dissertation can be used to help implement light weight, less formable materials into automotive products.
- The appendices at the end of this dissertation outline the detailed procedures to develop the analytical and numerical tools and can be helpful to anyone who wishes to follow this work.

7.4 Future Work

The author of this dissertation proposes the following items as future work:

- Develop an analytical method to predict time and location variable BHF profiles for rectangular and asymmetric panels.
- Continue the numerical investigation of implementing a feedback loop into commercial FEM software (adaptive simulation) for the purpose of predicting optimal time and location variable BHF profiles and validate with laboratory experiments.
• Conduct adaptive simulations and experiments with the non-flat rectangular panel tooling and hydraulic BHF control system.

• Conduct adaptive simulations on industrial parts and validate with industrial experiments.

• Implement failure criteria into a commercial FEM program and validate with laboratory experiments.

• Beta test the proposed design methodology and interactive modules at an industrial site and use the results to improve the methodology.
REFERENCES


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Wong, W., Publisher. (1968) Luders Lines in Cold Worked 5252.


APPENDIX A

REFERENCE EQUATIONS FOR DEEP DRAWING

A.1 Round Cup Deep Drawing

The drawing force \( (F_d) \) can be calculated using the following equation derived by Siebel (1955). Please refer to Figure 2.40 for a description of the symbols used for round cups.

\[
F_d = (\pi d_w f_0) \left[ e^{0.5\mu} \left( 1.0\sigma_f \ln \frac{d_f}{d_w} \right) + \left( \frac{2\mu F_h}{\pi d_f f_0} \right) + \left( \frac{\sigma_d f_0}{2r_d} \right) \right] \tag{Equation A.1}
\]

(Siebel, 1955)

The first term in the large brackets of Equation A.1 captures the force to overcome friction at the die radius. The second term calculates the force to overcome the compressive forces in the flange. The third term takes into account the friction at the blank holder/sheet interface. The final term calculates the bending forces at the die radius. Equation A.1 does not take into account the anisotropy of the sheet or the evolution of the wrap angle around the die radius.

Equation A.1 calculates the drawing forces at any stage of the process. The term \( d_f \) refers to the instantaneous flange diameter at the desired stage of deep drawing and can be calculated by assuming contancy of volume and no thickness change.

\[
d_f = \sqrt{d_0^2 - 4d_h h} \tag{Equation A.2}
\]

In order to use Equation A.1, the average flow stress in the flange (\( \sigma_f \)) and die radius (\( \sigma_d \)) must be calculated. This is done by calculating the strain at points 1, 2, and 3 as shown in Figure 2.41 and using the flow stress equation \( \bar{\sigma} = K[\bar{\varepsilon}_0 + \bar{\varepsilon}]'' \) to calculate the stresses at
these points. The average flange flow stress is calculated by averaging stresses 1 and 2 and the average flow stress over the die radius is the average of stresses 2 and 3.

The strains and stresses at points 1, 2 and 3 and the average flow stresses can be calculated using the following equations:

\[
\varepsilon_1 = -\ln \frac{d_1}{d_0}
\]  
(Equation A.3) (Siebel, 1955)

\[
\varepsilon_2 = \ln \frac{\sqrt{d_0^2 + (d_d + 2r_d)^2} - d_1}{d_d + 2r_d}
\]  
(Equation A.4) (Siebel, 1955)

\[
\varepsilon_3 = \varepsilon_2 + \ln \left(1 + \frac{t}{2r_d + t}\right)
\]  
(Equation A.5) (Siebel, 1955)

\[
\sigma_1 = K(\varepsilon_1 + e_0)^n
\]  
(Equation A.6) (Siebel, 1955)

\[
\sigma_f = 0.5(\sigma_1 + \sigma_2)
\]  
(Equation A.7) (Siebel, 1955)

\[
\sigma_d = 0.5(\sigma_2 + \sigma_3)
\]  
(Equation A.8) (Siebel, 1955)

Siebel derives the friction around the die radius as follows. The model and conventions used are shown in Figure 4.3 which is essentially the rope-pulley friction model.

Radial direction: \(dN - f \sin \left(\frac{d\alpha}{2}\right) - \left(F + dF\right) \sin \left(\frac{d\alpha}{2}\right) = 0\)

Replace \(\sin \left(\frac{d\alpha}{2}\right)\) with \(\frac{d\alpha}{2}\); \(dN - Fd\alpha = 0\)

Tangential direction: \(dF = dR = \mu dN\)

Combine: \(\frac{dF}{F} = \mu d\alpha\)  
(Equations A.9)  
(Siebel, 1995)

Integrate: \(\ln \left(\frac{F_2}{F_1}\right) = \mu \alpha\)

Isolate: \(F_2 = F_1 e^{\mu \alpha}\)

Since die radius is very small compared to cup diameter:

\[
\sigma_2 = \sigma_1 e^{\mu \alpha}
\]
Where $\sigma_r$ is the radial stress at the entrance of the die radius and $\sigma_e$ is the radial stress at the exit of the die radius.

### A.2 Rectangular Pan Deep Drawing

To design a blank for a rectangular panel with vertical walls and a flange, a more involved procedure must be used. The width ($w_0$) and length ($l_0$) of the blank are calculated by unfolding the length and width sections of the panel. The corner radius ($r_0$) of the blank is calculated by assuming the corner of the panel is a round cup. The dimensions of the blank are then adjusted using empirical based formulas to take into account the actual deformation patterns of rectangular panels.

This procedure and the equations were outlined by Lange (1985), but the author of this dissertation found the predictions to be inadequate. Upon inspection, the equations seemed to be inconsistent with the outlined procedure. The analytical equations were reformulated based on Lange’s stated procedure and the empirical equations were retained. The new formulations predicted blank shapes more accurately when compared to a one-step FEM simulation as shown in Table 2.2. Please refer to Figure 2.42 for a description of the symbols used for rectangular pans.

\[
\begin{align*}
    l_0 &= l_1 + 2h + 2f - 2\Delta l_0 \\
    w_0 &= w_1 + 2h + 2f - 2\Delta w_0 \\
    c_0 &= \left( \frac{0.5(l_0 - l_1) + r_1}{\sqrt{2}} \right)^2 + \left( \frac{0.5(w_0 - w_1) + r_1}{\sqrt{2}} \right)^2 - r_0 \\
    r_0 &= \frac{c_0}{2\left(1 - \frac{1}{\sqrt{2}}\right)} \\
    r_0'' &= 0.5\sqrt{4(r_1 + f)^2 + 8r_1h}
\end{align*}
\]
Where $\Delta l_0$, $\Delta w_0$, and $r_0'$ are calculated from Lange's empirical equations (1985).

\[
k = 0.74 \left( \frac{r_0'''}{2 r_1} \right)^2 + 0.982
\]

\[
\Delta l_0 = \frac{y r_0'''}{w_i - 2 r_i}
\]

\[
r_0' = k r_0'''
\]

\[
y = \frac{\pi r_0'''}{4}
\]

\[
\Delta w_0 = \frac{y r_0'''}{l_1 - 2 r_i}
\]

(Equations 2.15) (Lange, 1985)

A.3 Elasticity Equations for Cylinder/Blank Holder Contact

The blank holder can be designed as one-piece and elastic. The contact of a cylinder piston and an elastic blank holder causes a pressure pattern at the blank holder/sheet interface as shown in Figure 2.23. This pressure pattern is high at the center of contact and decays exponentially radially outward. The effective range can be defined as the radius at which 90% of the BHF of the cylinder is inside.

If the effective range is too small then there will be regions of low BHP where the sheet will not be properly controlled. If the effective range is too large, then the actions of the cylinder will be coupled which will also cause a loss of independent control of the cylinders. Shulkin (1998) studied this problem and determined that for a given cylinder and blank holder, a proper effective range could ensured by calculating an appropriate blank holder thickness.

Shulkin (1998) developed equations which determines the pressure pattern which is developed in the simplified cylinder/blank holder model in Figure 2.23.

\[
\sigma_{zz}(r, z) = \int_0^\infty \frac{\xi F(\xi)}{d(\beta)} \left\{ -\left[ \xi z S^2 + (\beta + SC) \right] S_z + \left[ S^2 - \beta^2 + \xi z (\beta + SC) \right] C_z + \right. \\
+ \left. \frac{h^4}{6 \beta ^4} \left[ -\left( \xi z SC + S^2 \right) S_z + \left( SC + \beta + \xi z S^2 \right) C_z \right] \right\} I_0(\xi \varphi) d\xi
\]

(Equation A.16)
Where \(d(\beta), S, C, S_z, C_z, \beta, F(\xi)\) and \(l\) are given as:

\[
d(\beta) = \sinh^2 \beta - \beta^2 + \frac{h^4}{6\beta l^4} (\beta + \sinh \beta \cosh \beta)
\]

\[
S = \sinh \beta, \quad C = \cosh \beta, \quad S_z = \sinh \xi_z, \quad C_z = \cosh \xi_z, \quad \beta = \xi h
\]

\[
F(\xi) = -\int_0^\infty p(r) \cdot r \cdot J_0(\xi r) dr
\]  
(Equations A.17)

\(p(r)\) is the input pressure function, \(p(r) = p(r)\) for \(0 \leq r \leq c\) and \(p(r) = 0\) for \(r > c\), and \(l\) is given by

\[
l = \frac{Eh}{\sqrt{12 (1 - \nu^2) k}}
\]  
(Equation A.18) (Shulkin, 1998)

Shulkin (1998) implemented these equations into a computer program to be used as a tool for proper elastic blank holders design. Also, the degree of coupling or dependency of the cylinders can be determined with this program. For example if the effective range was designated as \(r_e\) and the distance between cylinders one and two were \(x_{12}\), then a coupling factor, \(f_c\), can be defined as follows:

\[
f_c = \frac{2r_e - x_{12}}{x_{12}}
\]  
(Equation A.19)

Thus for \(f_c \leq 0\), the cylinders are uncoupled. For \(0 < f_c < 1\), the cylinders are partially coupled. For \(f_c \geq 1\), the cylinders are fully coupled.
APPENDIX B

INSTRUCTIONS FOR SHEET FORMING DESIGN SYSTEM

The sheet forming design system is a spreadsheet which is divided into 26 sheets as shown in Figure B.1. Each sheet is either a user interface for a particular calculation or a graphical display of calculation results. In particular, the following calculations may be made with the sheet forming design system:

- Round Cups and Rectangular Pan Deep Drawing
- Optimal BHF Time Profiles
- Minimum and Maximum Constant BHF
- Load Versus Stroke
- Limiting Draw Ratio
- Drawbead Forces and Geometry
- Blank Shapes
- Forming Limit Diagrams
- Units Conversion
- Material Data
- Flow Stress Curve Fitting

Figures B.2 and B.3 shows the user interface for the optimal BHF profile and load versus stroke calculator and for round cups, while Figures B.4 and B.5 are the same for rectangular pans. Figure B.6 shows the drawbead geometry calculator worksheet while Figure B.7 contains the blank shape calculation worksheet.

All interfaces are similar in format and use consistent conventions. The green colored areas indicates the user input areas. In particular, green colored boxes indicated required input data. Generally, there will be two green areas - one for material data and the other
for tool geometry. Useful values which are calculated by the spreadsheet are included in red colored areas.

Grey areas indicate intermediate calculated values which are not necessary for the general user. Important instructions are included in orange boxes and yellow boxes indicate advanced solution techniques are required. The advance techniques are outlined in the orange areas for the user's convenience. The required units are always indicated and schematics are included to explain the meaning of terminology used in the module. Each sheet is formatted for easy printing and contains the current date and time for the convenience of the user.

Figure B.1: Instruction page in the sheet forming design system
Figure B.2: Round cup optimum BHF profile worksheet of sheet forming design system

Figure B.3: Round cup load versus stroke worksheet of the sheet forming design system
### Figure B.4: Rectangular pan optimum BHF profile worksheet of sheet forming design system

<table>
<thead>
<tr>
<th>Material Data</th>
<th>Optimal BHF Versus Stroke Generator</th>
<th>Siebel/Thomas Drawing Load Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type</td>
<td>Alum</td>
<td>Alum</td>
</tr>
<tr>
<td>K-value (psi)</td>
<td>70,000</td>
<td>70,000</td>
</tr>
<tr>
<td>n-value</td>
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<td>2,322</td>
</tr>
<tr>
<td>e-value</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>v-value</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>Young's Mod. E (psi)</td>
<td>100,000,000</td>
<td>100,000,000</td>
</tr>
<tr>
<td>Thickness (inch)</td>
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<td>0.04</td>
</tr>
<tr>
<td>Cracking Factor (r-1)</td>
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<td>0.9</td>
</tr>
<tr>
<td>Stress Distribution (r)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Blank Length (inch)</td>
<td>24.8</td>
<td>24.8</td>
</tr>
<tr>
<td>Blank Width (inch)</td>
<td>22.7</td>
<td>22.7</td>
</tr>
<tr>
<td>Corner Cut (inch)</td>
<td>6.75</td>
<td>6.75</td>
</tr>
<tr>
<td>Corner Radius (inch)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Figure B.5: Rectangular pan load versus stroke worksheet of the sheet forming design system

<table>
<thead>
<tr>
<th>Material Data</th>
<th>Load Versus Stroke Generator</th>
<th>Siebel/Thomas Drawing Load Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Type</td>
<td>Alum</td>
<td>Alum</td>
</tr>
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<td>70,000</td>
</tr>
<tr>
<td>n-value</td>
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<td>0</td>
</tr>
<tr>
<td>v-value</td>
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<td>0.84</td>
</tr>
<tr>
<td>Young's Mod. E (psi)</td>
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<td>100,000,000</td>
</tr>
<tr>
<td>Thickness (inch)</td>
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</tr>
<tr>
<td>Cracking Factor (r-1)</td>
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<td>0.9</td>
</tr>
<tr>
<td>Stress Distribution (r)</td>
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<td>0.05</td>
</tr>
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<tr>
<td>Blank Width (inch)</td>
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<tr>
<td>Corner Radius (inch)</td>
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</tbody>
</table>

<table>
<thead>
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<th>Load Versus Stroke</th>
<th>Flange Strain 1</th>
<th>Flange Strain 2</th>
<th>Siebel/Thomas Drawing Load Analysis</th>
</tr>
</thead>
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<td>Stress 2</td>
<td>Alum</td>
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<td>0.00</td>
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<td>0.00</td>
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<tr>
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<td>0.00</td>
<td>0.00</td>
<td>50446</td>
</tr>
</tbody>
</table>

### Table Data

<table>
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<th>Material Number</th>
<th>Punch Length (inch)</th>
<th>Punch Width (inch)</th>
<th>Punch Corner Rad (in)</th>
<th>Punch Radius (inch)</th>
<th>Die Length (inch)</th>
<th>Die Width (inch)</th>
<th>Die Corner Rad (in)</th>
<th>Die Radius (inch)</th>
<th>Draw Depth (inch)</th>
<th>Friction (u)</th>
<th>Drawhead Force (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.946</td>
<td>11.99</td>
<td>2.95</td>
<td>0.39</td>
<td>15.098</td>
<td>12.142</td>
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<td>5</td>
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</tr>
<tr>
<td>2</td>
<td>14.946</td>
<td>11.99</td>
<td>2.95</td>
<td>0.39</td>
<td>15.098</td>
<td>12.142</td>
<td>3</td>
<td>0.39</td>
<td>5</td>
<td>0.1</td>
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</tr>
<tr>
<td>3</td>
<td>14.946</td>
<td>11.99</td>
<td>2.95</td>
<td>0.39</td>
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<td>12.142</td>
<td>3</td>
<td>0.39</td>
<td>5</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
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<td>11.99</td>
<td>2.95</td>
<td>0.39</td>
<td>15.098</td>
<td>12.142</td>
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<td>0.39</td>
<td>5</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>14.946</td>
<td>11.99</td>
<td>2.95</td>
<td>0.39</td>
<td>15.098</td>
<td>12.142</td>
<td>3</td>
<td>0.39</td>
<td>5</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table Data

<table>
<thead>
<tr>
<th>Material Number</th>
<th>UL Tens (psi)</th>
<th>Max Draw Load (lbf)</th>
<th>Equiv Blank (inch)</th>
<th>Equiv Punch (inch)</th>
<th>Equiv Die (inch)</th>
<th>Equiv Pan Dia (inch)</th>
<th>Punch/Shear Clear (in)</th>
<th>Equiv Cup (inch)</th>
<th>Radius of Punch (in)</th>
</tr>
</thead>
</table>
Figure B.6 Drawbead geometry worksheet of the sheet forming design system

Figure B.7: Blank shape worksheet of the sheet forming design system
APPENDIX C

INSTRUCTIONS FOR COMPILING ROUTINES
INTO THE FEM CODE PAM-STAMP

Engineering Systems International (ESI) has provided the author of this dissertation with the means to implement subroutines into Pam-Stamp. This subroutine would be executed at every timestep and allows the user the ability to modify any velocity or force profile based on the forming conditions. The forming conditions that could be accessed through the subroutine are:

1. current time
2. nodal coordinates
3. nodal displacement
4. nodal velocity
5. nodal acceleration
6. elemental strain
7. elemental thinning
8. elemental stress
9. contact force

The following files were provided by ESI.

1. ldcmod.f
2. v98.102.a
3. makefile
4. PC_INIT

The first file named "v98.102.a" is a library containing the Pam-Stamp core solver program. The second file named "ldcmod.f" is the user subroutine. The "makefile" is a batch file which executes the commands to compile the core program with the user subroutine. The "PC_INIT" file contains the license which will be required to run the
adaptive simulation. There is an expiration date on the license, so any renewal requests should be directed to ESI.

The user subroutine is programmed in Fortran. The user has any Fortran command at his or her disposal. In addition, the following commands are provided by ESI to the user:

**DXYZ**: Array of nodal coordinates  
**DISP**: Array of nodal displacements  
**VEL**: Array of nodal velocities  
**ACC**: Array of nodal accelerations  
**INOD(N)**: External number of internal node number N  
**ISHEL(N)**: External number of internal element number N  
**IMAT(N)**: External number of internal material number N  
**TIME**: Current time of simulation  
**NUMCON**: Number of contact interfaces  
**CONFORCE(1,N)**: Contact force X-direction of contact interface N  
**CONFORCE(2,N)**: Contact force Y-direction of contact interface N  
**CONFORCE(3,N)**: Contact force X-direction of contact interface N  
**NUMNOD**: Number of nodes  
**LABNOD(N)**: External node number of internal node number N  
**NUMSHE**: Number of shell elements  
**LABSHE(N)**: External element number of internal element number N  
**KONSHE(N,M)**: For N=1, the internal material number is returned for element M. For N=2,3,4,5, the internal node numbers of element M are returned. For N=6, the number of through thickness integration points of internal element M is returned.  
**INDEX(N)**: Address of internal element N in the index table.  
**STRTAB(N)**: Return various strain and stress values from the index table.  
**NUMCUR**: Number of velocity and forces curves  
**LABCUR(N)**: External curve number of internal curve number N  
**FUNVAL(N)**: Current value of internal curve N
MATTYP(N): Material type of internal material number N
CCM(N,M): For N=68,69,70, returns the G, F, and N values from Hill's Yield Function for internal element M.

ESI has also provided a routine which iteratively returns various strain and stress values for each and every element successively in a DO loop. The various values and their names are listed below.

THO: Original thickness
THK: Current thickness
THN: Current thinning
S1(I): Normal stress in the X-direction for integration point I
S2(I): Normal stress in the Y-direction for integration point I
S3(I): Shear stress integration point I
LSIG11: Lower surface normal stress in the X-direction
LSIG22: Lower surface normal stress in the Y-direction
LSIG12: Lower surface shear stress
USIG11: Upper surface normal stress in the X-direction
USIG22: Upper surface normal stress in the Y-direction
USIG12: Upper surface shear stress
MSIG11: Middle surface normal stress in the X-direction
MSIG22: Middle surface normal stress in the Y-direction
MSIG12: Middle surface shear stress
MSIG1: Middle surface first principal stress
MSIG2: Middle surface second principal stress
MEPSPL: Middle surface plastic strain
LEPS11: Lower surface normal strain in the X-direction
LEPS22: Lower surface normal strain in the Y-direction
LEPS12: Lower surface shear strain
UEPS11: Upper surface normal strain in the X-direction
UEPS22: Upper surface normal strain in the Y-direction
UEPS12: Upper surface shear strain
STRESSEQ: Equivalent stress

Please note that the elemental values above correspond to the local coordinate system of each element. ESI has also provided a routine which will find the maximum stress in the sheet at every time step, the element number of this maximum stress, and the coordinates of the center of gravity of this element. The variables used are:

STRESSMAX: Value of the maximum stress in the sheet
NBSHEMAX: Internal element number of the maximum stress
XCOG: Coordinate X of the center of gravity of the maximum stress element
YCOG: Coordinate Y of the center of gravity of the maximum stress element
ZCOG: Coordinate Z of the center of gravity of the maximum stress element

One thing to keep in mind is that Pam-Stamp renumbers nodes, elements, materials, and curves internally. Therefore, if you want to get the stress of element 100. Then you must find the internal numbering of the external element 100 by using the command "ISHEL".

Finally, ESI has provided a routine which accesses the current value of any force or velocity curve and modifies it for the next timestep. The following variable is used in the routine:

NCURSL: The external number of the curve to be modified.

Nuri Akgerman has provided the author with a subroutine which finds the next uncommented line in a text file. This is very useful to read data from a configuration file. The command structure is as follows:
GETNXTLN (LUN, CMNT_CHR, LINE_BUF, EOFLAG): Gets the next uncommented line number in the file "LUN" and returns the value in "LINE_BUF". The character used as the comment indicator should be placed instead of "CMNT_CHR" and the end of file flag should be placed instead of EOFLAG (typically "EOF").

The GETNXTLN routine is included below. This subroutine should be appended to every user subroutine included in the next four appendices.

```c
SUBROUTINE getnxtln ( LUN, CMNT_CHR, LINE_BUF, EOFLAG )
C
C Gets the next data line from LUN that is not a comment
C Used by routines that read configuration files
C N.Akgerman, Feb 1988
C
C     LUN     : Logical unit number
C     CMNT_CHR : Comment character, usually a # sign
C     LINE_BUF : Input line buffer
C     EOFLAG   : End-Of-File flag
C
LOGICAL   EOFLAG
INTEGER*4  LUN
CHARACTER*1 CMNT_CHR
CHARACTER*80 LINE_BUF
C
C------------------------------------------------------------------------
C
C  EOFLAG = .FALSE.
C
C  DO 10 I = 1, 80
C   LINE_BUF(I:I) = ',
C  10   CONTINUE
C
C  25  CONTINUE
C      READ ( LUN, 30, END=90 ) LINE_BUF
C  30  FORMAT ( A80 )
C      IF ( LINE_BUF(1:1) .EQ. CMNT_CHR ) GO TO 25
C
C  RETURN
C
C------------------------------------------------------------------------
C
C  90  CONTINUE
C  EOFFLAG = .TRUE.
C  RETURN
C  END
C
C FUNCTION LLLEN ( STRNG )
C Determine the actual printable length
C C
C CHARACTER*(*) STRNG
C
C------------------------------------------------------------------------
C
C     N = LEN ( STRNG )
C
C Search forward for a null byte
```

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The author has added two more files to the adaptive simulation system as follows:

1. control.prm
2. *.log

The "control.prm" file contains various configuration values for the adaptive simulation. These values vary for each control strategy and will be discussed individually in the next four appendices. The "control.prm" also provides the user with the opportunity to designate the name of the output *.LOG file. The adaptive simulation will fill this output log file with important values calculated during the adaptive simulation. Again, this will be discussed in depth in the next four appendices.

In addition to this, the author of this dissertation has defined several other variables that are related to the specific control strategy. The common variables are listed here while the specific control variables will be discussed in the next four appendices. We will begin with the user specified variables:

STARTTIME: User specified timestep value to begin control.
ENDTIME: User specified timestep value near the end of the simulation used to determine the linear variation of the setpoint if specified.
N_TH: User specified static averaging window size.
MOVE: User specified moving averaging window size.
KP: User specified proportional constant for the PID controller.
KI: User specified integral constant for the PID controller.
KD: User specified derivative constant for the PID controller.
MINBHF: User specified minimum BHF.
MAXBHF: User specified maximum BHF.

The following are the calculated common variables that have been designated by the author.

TIMESTEP: Current timestep value (incremented every time the user subroutine is called).
NTMS: Static averaging window counter.
ERROR: Current error value or proportional value of the PID controller (=setpoint-measurement).
SUMERROR: Current summated error value or integral value of the PID controller (=sumerror+error).
SLOPE: Current slope value or derivative value of the PID controller (= current measurement - previous measurement).
AVGERROR: Current summated error value to be used for static averaging and is reset everytime the static averaging window is renewed.
DELTABHF: Current BHF modification as specified by the PID controller (=KP*ERROR+KI*SUMERROR+KD*SLOPE).
BHFHISTORY: The current summated DELTABHF to be used to modify the FUNVAL(N) or BHF profile (=BHFHISTORY+DELTABHF).
BHFINITIAL: The initial value of the BHF used to ensure that the BHFHISTORY does not obtain a value which violates the MINBHF and MAXBHF.
PAMBHF: The current value of the BHF profile from Pam-Stamp used to output to the *.LOG file.

If a user want to develop his or her own control strategy, then he or she may develop a new user subroutine "ldcmod.f". Once this new subroutine is created then it must be compiled by executing an "f77" on the user subroutine and then compiling by executing
the make file. Thus make sure that the current directory contains the user subroutine, the "makefile" and the Pam-Stamp core library. Thus the sequence of commands are:

    f77 ldcmod.f
    make
    rm a.out

No error should be indicated after any of these commands. Ignore any warnings as they are permitted. This procedure will create an executable file named "v98.102.x" which contains the Pam-Stamp core solver embedded with the new user subroutine. Please note, that the user subroutine variable "FUNVAL(N)" is the current value of the force curve only. Thus, if the user is modifying these values as part of the control scheme, the user must remember to modify these values every timestep as if from the starting value.

If a user wants to run an adaptive simulation on an existing Pam-Stamp input deck (typically *.ps), then he or she must configure "control.prm" configuration file as necessary. Once this is complete, the adaptive simulation may be executed in C shell on a unix workstation. The environment variable "PCHOME" must be pointed to the directory containing license file provided by ESI. Then adaptive simulation executable file "v98.102.x" must be executed. Thus the sequence of commands are:

    csh
    setenv PCHOME path
    ./v98.102.x <*.ps >*.out &

Please keep in mind, that the user must be aware of which control strategy he or she would like to use, since all executable files have the same name but different control methods. Typically, the directory which contains the executable has a descriptive name indicating the control method.
There are several requirements for the adaptive simulation. First, the specified "STARTIME" should be a value equal to or greater than the moving averaging window size (MOVE) which should be in turn be greater than or equal to the static averaging window size (N_TH). The "MINBHF" should not be less that zero and the "MAXBHF" should not be larger than the maximum force allowable by the contact model. If a larger "MAXBHF" is necessary then the user should input a larger contact penalty.

Also, there are several requirements for the setup of the FEM model for an adaptive simulation. First, the press must be double action. That is the die surface must be stationary, the binder surface must apply a constant force onto the die, and the punch must travel with a velocity boundary condition into the sheet and die cavity. The stamping direction and punch movement must be in the positive Z-direction. The die surface must be entirely in the positive Z space with the lowest portion of the die surface at Z=0. The remaining tools are arranged accordingly from there. See Figure C.1 for an illustrated example.

Each of these feedback routines modify curve number 2. Therefore, the user should make sure that the nodal force BHF boundary condition be defined with curve number 2, or else the control will not work correctly. The scalar value of the nodal force should be equal to one and curve 2 should contain the actual BHF values which should be of constant value during the control sequence. The user should renumber the nodes, elements, materials, curves, and contact interfaces sequentially beginning from one. There are automatic routines in the Pam-Stamp preprocessor. Future, the user should remember to set \( \varepsilon_0 \) greater than zero when using Krupkowski's flow law, \( \sigma = K(\varepsilon + \varepsilon_0)^n \). The final restriction is that the adaptive simulation is developed only for sheet material models 107 or 109 with reduced integration (see Pam-Stamp manuals).
Figure C.1: Required configuration for tool surfaces in an adaptive simulation
APPENDIX D

INSTRUCTIONS FOR WRINKLING BASED ADAPTIVE SIMULATION

At each time step, this algorithm attempts to maintain the gap between the binder surfaces at a predetermined setpoint by actively varying the blank holder pressure (BHP) using a PID controller. This strategy should produce a BHF profile which ensures no wrinkling, minimizes final part strain and fracture. This algorithm allows the user to specify:

- $k_p$, $k_i$, $k_d$ controller constants
- static and moving average filtering window sizes
- minimum and maximum BHF
- start time for control
- any linearly changing setpoint of binder gap for up to three different binder segments

The optimal values of $k_p$, $k_i$, $k_d$, and filtering parameters have been determined to maximize control robustness. They are as follows:

$$KP = 0.001$$
$$KI = 0.0$$
$$KD = 0.0$$
$$N\_TH = 100$$
$$MOVE = 100$$

The minimum and maximum BHP levels should be set according to press and tool capacity. The start time should be set soon after deep drawing has begun typically after
2-3% of the draw depth has been achieved. It has been determined that the initial value of the binder gap setpoint should be 10% greater than the initial material thickness and the final value of the binder gap setpoint should be 10% greater than the final maximum thickness of the part. In general, a variation of binder gap setpoint from 1.1t to 1.5t, where t is the original material thickness, is sufficient. The binder gap strategy should produce a BHF profile which minimizes final part stretch while avoiding wrinkling.

This is the only user routine which controls the blank holder pressure rather than the blank holder force. It was found that the optimal values for the controller constants \( k_p, k_i, k_d \) were functions of the binder surface area. Thus, by controlling the BHP rather than the BHF, control stability was improved and a unique set of \( k_p, k_i, k_d \) were found. Thus the user should keep in mind to define a static pressure to the binder surface or surfaces rather than a nodal force. If only one binder segment is to be controlled, then the static pressure for this segment should be defined with curve number 2. If two or more binder segments are to be controlled, then define static pressures for binder segment 2 with curve number 3 and binder segment 3 with curve number 4.

Thus the previously defined variable, MINBHF, MAXBHF, DELTABHF, BHFHISTORY, BHFINITIAL, and PAMBHF are actually pressure instead of force. The minimum and maximum BHP should be set to 0.0 and 1.0 GPa. Due to the intrinsic nature of this control scheme, violent vibrations are imparted onto the system. In order to reduce contact problems, the penalty contact values for the binder-sheet and die-sheet interfaces should be set to 0.1.

The following user specified variables are defined for this control algorithm:

STARTGAP: User specified initial binder gap setpoint Z position.
ENDDGAP: User specified final binder gap setpoint Z position.
NODE(N): User specified external node number contained in the binder segment N to be controlled.
POINTS: User specified number of binder segments to be controlled (up to three).

The following calculated variables are defined for this control algorithm:

GAP: Current binder gap setpoint distance calculated based on the line from the point (STARTGAP, STARTIME) to the point (ENDGAP, ENDTIME).
INODE(N): Internal node numbers corresponding to NODE(N)
ZPOS(N): Current Z coordinate position of the binder segment N.
AVGZPOS(N): Summated Z coordinate position of binder segment N reset everytime static averaging window is renewed.
PREVZPOS(N): Previous averaged Z position of binder segment N.
ALLZPOS(N,M): An array of all Z positions for binder segment M for timestep N.

The configuration file "control.prm" takes the following format:

```
# Control Parameter file. The first line contains
# KP, KI, KD, MINBHP, MAXBHP, M_TH, M_OVE, NODE(1) (3F10.5, 2F10.1, 3I10)
#234567890123456789012345678901234567890123456789012345678901234567890
0.00100  0.00000  0.00000  0.0  1.0  100  100  1800
# Extra Parameters
# STARTGAP, ENDGAP, STARTIME, ENDTIME, POINTS, NODE(2), NODE(3) (2F10.3, 5I10)
#234567890123456789012345678901234567890123456789012345678901234567890
-1.100  -1.500   500   60000   3  2000   2300
# This is the name of the output file, up to 40 characters
rect3-p2.log
```

Please note that the format and positions of the numbers are precise and are indicated in the commented areas. These number formats are standard Fortran number formats. For example, a format "3F10.5" indicates that there are 3 floating point numbers which are 10 characters long (including decimal and sign) which have five digits after the decimal place. The format "5I10" indicates that there are five integers with 10 characters each (including decimal and sign).

The output *.LOG file takes the following format:
The user may make a plot of TIME versus GAP, ZPOS1, PAMBHF1, ZPOS2, PAMBHF2, ZPOS3, and PAMBHF3 to see the control action visually. It is best to format the graph so that GAP and ZPOS(N) are on one axis scale while PAMBHF(N) are on another.

The user subroutine for the binder gap/wrinkling algorithm is included below. The user may find these files in the directory "Pressure" in the author's files. Remember to append the subroutine GETNXTLN from Appendix C.

```c
C**********************************************************************
C Binder Gap/Wrinkling User Subroutine
C**********************************************************************
SUBROUTINE LDCMOD (NUMNOD, LABNOD, DXYZ, DISP, VEL, ACC, NUMSHE, 
  . LABSHE, KONSHE, INDEX, STARTAB, NUMCUR, LABCUR, 
  . FUNVAL, MPTYP, CCM, NNP, INOD, ISHEL, IMAT, 
  . TIME, NUMCON, CONFORCE)
```
REAL LSIG11,LSIG22,LSIG12,MSIG11,MSIG22,MSIG12,KMID1,KMID2,
MESP,LEPS11,LEPS22,LEPS12,DXYZ,DISP,VEL,ACC,CCM,G,F,N,H
COMMON/AUX40/S1(48),S2(48),S3(48)
DIMENSION LABNOD(*),DXYZ(3,*),LABSHE(*),KONSHE(6,*),INDEX(*),
DISP(3,*),VEL(3,*),ACC(3,*),STRTAB(*),LABCUR(*),
FUNVAL(*),MATTYP(*),CCM(NNPROP,*),ISHEL(*),INOD(*),
IMAT(*),CONFORCE(5,*)

C
C*******************************************************************************************
C Control Parameters
C*******************************************************************************************
C
REAL KP, KI, KD, MINBHF, MAXBHF, STARTGAP, ENDGAP
INTEGER STARTIME, ENDTIME, NODE(1:3), N_TH, MOVE, TIMESTEP
INTEGER LOOP, COUNT, POINTS, INODE(1:3)
REAL ERROR(1:3), SUMERROR(1:3), SLOPE(1:3), GAP
REAL DELTABHF(1:3), BHPHISTORY(1:3), PAMBHF(1:3)
REAL ZPOS(1:3), AVGZPOS(1:3), PREZPOS(1:3), BFINITIAL(1:3)
REAL ALLZPOS(1:3,1:100000)
LOGICAL FIRST_TIME, EOF
INTEGER LUNPRM, LOG, IOS, NCHR, NTMS
CHARACTER*40 FILE_NAME
CHARACTER*80 LINE
C
DATA KP, KI, KD/ 0.0, 0.0, 0.0/, STARTGAP/ 0.0/
DATA MINBHF/ 0.0/, MAXBHF/ 0.0/, ENDGAP/ 0.0/, POINTS/ 0/
DATA STARTIME/ 0/, NODE/ 3*0/, N_TH/ 0/, MOVE/ 0/, TIMESTEP/ 1/
DATA LOOP/ 0/, ERROR/ 3*0.0/, SUMERROR/ 3*0.0/, SLOPE/ 3*0.0/
DATA DELTABHF/ 3*0.0/, BHPHISTORY/ 3*0.0/, PAMBHF/ 3*0.0/
DATA ZPOS/ 3*0.0/, AVGZPOS/ 3*0.0/, PREZPOS/ 3*0.0/
DATA ALLZPOS/ 300000*0.0/, ENDTIME/ 0/, GAP/ 0.0/, INODE/ 3*0/
DATA FILE_NAME/ /, NTMS/ 0/, LUNPRM/ 77/, COUNT/ 0/
DATA FIRST_TIME/.TRUE./, LOG/ 78/, BFINITIAL/ 3*0.0/
C
C*******************************************************************************
C OBJECTIVE: Find of the position of the binder and modify the BHF to
C ensure that wrinkling does not occur in the flange and to minimize
C fracture and final part strain.
C
C Read input values from "control.prm"
C*******************************************************************************
C
IF ( FIRST_TIME ) THEN
OPEN ( LUNPRM, FILE='control.prm', IOSTAT=IOS )
IF ( IOS.NE.0 ) THEN
WRITE ( *, 10 )
FORMAT( 'Could not open control.prm' )
STOP
ENDIF
C
CALL getnxtln ( LUNPRM, '#', LINE, EOF )
READ ( LINE, 20 ) KP, KI, KD, MINBHF, MAXBHF, N_TH, MOVE, NODE(1)
20 FORMAT( 3F10.5, 2F10.1, 3I10 )
CALL getnxtln ( LUNPRM, '#', LINE, EOF )
READ ( LINE, 30 ) STARTGAP, ENDGAP, STARTIME, ENDTIME, POINTS,
* NODE(2), NODE(3)
30 FORMAT( 2F10.3, 5I10 )
C
C Get the name of the output/log file
C
CALL getnxtln ( LUNPRM, '#', LINE, EOF )
NCHR = LLEN ( LINE )
FILE_NAME = LINE(1:NCHR) // CHAR(0)

CLOSE ( LUNPRM )
FIRST_TIME = .FALSE.
C
Open the log file
C
OPEN ( LOG, FILE=FILE_NAME, IOSTAT=IOS )
WRITE ( LOG, 40 ) KP, KI, KD, MINBHF, MAXBHF
40 FORMAT ( 'KP, KI, KD, MINBHF, MAXBHF:', 3F10.5, 2F10.1 )
WRITE ( LOG, 50 ) N_TH, MOVE, NODE(1), NODE(2), NODE(3)
50 FORMAT ( 'N_TH, MOVE, NODE1, NODE2, NODE3:', 5I10 )
WRITE ( LOG, 60 ) STARTGAP, ENDGAP, STARTTIME, ENDTIME, POINTS
60 FORMAT ( 'STARTGAP,ENDGAP,STARTTIME,ENDTIME,POINTS:' , 2F10.3, 3I10 )
WRITE ( LOG, 70 )
70 FORMAT ( ' ', TIMESTEP, TIME, GAP, ERROR1, SUMERROR1, SLOPE1, DELTABHF1, ' ',
* 'BHPHISTORY1, ZPOS1, PAMBHF1, ERROR2, SUMERROR2, SLOPE2, ' ,
* 'DELTABHF2, BHPHISTORY2, ZPOS2, PAMBHF2, ERROR3, SUMERROR3, ' ,
* 'SLOPE3, DELTABHF3, BHPHISTORY3, ZPOS3, PAMBHF3' )
ENDIF
C
Get Z displacement of NODE
C******************************************************************************
C
DO 77 COUNT=1, NUMNOD
DO 73 LOOP=1, 3
   IF (INOD(COUNT) .EQ. NODE(LOOP)) INODE(LOOP) = COUNT
73   CONTINUE
77 CONTINUE
C
DO 80 LOOP = 1, POINTS
   ALLZPOS(LOOP, TIMESTEP) = DXYZ(3, INODE(LOOP))
80 CONTINUE
C******************************************************************************
C Proportional, Integral, Derivative Controller
C******************************************************************************
C
IF (TIMESTEP .GT. STARTTIME) THEN
   NTMS = NTMS + 1
   IF (NTMS .GE. N_TH) THEN
      DO 100 COUNT = 1, POINTS
         DO 90 LOOP = (TIMESTEP-MOVE+1), (TIMESTEP)
            AVGZPOS(COUNT) = AVGZPOS(COUNT) + ALLZPOS(COUNT, LOOP)
90         CONTINUE
         ZPOS(COUNT) = AVGZPOS(COUNT) / MOVE
100        CONTINUE
C
   DO 175 COUNT = 1, POINTS
      IF (PREZPOS(COUNT) .EQ. 0.0) THEN
         AVGZPOS(COUNT) = 0.0
         DO 150 LOOP = (TIMESTEP-MOVE-N_TH+1), (TIMESTEP-N_TH)
            AVGZPOS(COUNT) = AVGZPOS(COUNT) + ALLZPOS(COUNT, LOOP)
150        CONTINUE
      PREZPOS(COUNT) = AVGZPOS(COUNT) / MOVE
ENDIF
175 CONTINUE
C
GAP = STARTGAP+((ENDGAP-STARTGAP)/ENDTIME)*TIMESTEP
C
208
IF ( ABS(GAP) .GT. ABS(ENDGAP) ) GAP = ENDGAP

DO 200 COUNT = 1, POINTS
   ERROR(COUNT) = GAP - ZPOS(COUNT)
   SUMERROR(COUNT) = SUMERROR(COUNT) + ERROR(COUNT)
   SLOPE(COUNT) = ZPOS(COUNT) - PREZPOS(COUNT)
   PREZPOS(COUNT) = ZPOS(COUNT)
   AVGZPOS(COUNT) = 0.0
200  CONTINUE
NTMS = 0

C Now calculate the binder load adjustment DELTABHF.
C
DO 225 COUNT = 1, POINTS
   DELTABHF(COUNT) = KP*ERROR(COUNT) + KI*SUMERROR(COUNT) + KD*SLOPE(COUNT)
   BHPHISTORY(COUNT) = BHPHISTORY(COUNT) + DELTABHF(COUNT)
225  CONTINUE

C Adjust the binder load curve #2 thru 4 by BHPHISTORY(N).
C
DO 275 LOOP = 1, POINTS
   NCURSL = LOOP + 1
   DO 250 ICUR = 1, NUMCUR
      NCUR = LABCUR(ICUR)
      IF (NCUR .EQ. NCURSL) THEN
         IF (TIMESTEP.EQ.(STARTIME+N_TH))
            BHPHINITIAL(LOOP) = FUNVAL(ICUR)
         ENDIF
         FUNVAL(ICUR) = BHPHISTORY(LOOP) + FUNVAL(ICUR)
         IF (FUNVAL(ICUR) .LT. MINBHF) THEN
            FUNVAL(ICUR) = MINBHF
            BHPHISTORY(LOOP) = MINBHF - BHPHINITIAL(LOOP)
         ENDIF
         IF (FUNVAL(ICUR) .GT. MAXBHF) THEN
            FUNVAL(ICUR) = MAXBHF
            BHPHISTORY(LOOP) = MAXBHF - BHPHINITIAL(LOOP)
         ENDIF
         IF (ZPOS(LOOP) .GT. 10) THEN
            FUNVAL(ICUR) = 0.0
            BHPHISTORY(LOOP) = MINBHF - BHPHINITIAL(LOOP)
         ENDIF
         PMBHF(LOOP) = FUNVAL(ICUR)
      ENDIF
250  CONTINUE
275  CONTINUE

C Output to Log File
C
WRITE ( LOG, 300 ) TIMESTEP, TIME, GAP, ERROR(1), SUMERROR(1),
* SLOPE(1), DELTABHF(1), BHPHISTORY(1), ZPOS(1), PMBHF(1),
* ERROR(2), SUMERROR(2), SLOPE(2), DELTABHF(2), BHPHISTORY(2),
* ZPOS(2), PMBHF(2), ERROR(3), SUMERROR(3), SLOPE(3), DELTABHF(3),
* BHPHISTORY(3), ZPOS(3), PMBHF(3)
300 FORMAT( I10, 23(1h,F10.5) )
C
ENDIF
C
C Adjust the binder load curve #2 by DELTABHF again.
C
DO 350 LOOP = 1, POINTS
   NCURSL = LOOP + 1
DO 325 ICUR = 1, NUMCUR
   NCUR = LABCUR(ICUR)
   IF (NCUR.EQ.NCURSL) FUNVAL(ICUR) = BHF HISTORY(LOOP) + FUNVAL(ICUR)
   IF (ZPOS(LOOP) .GT. 10) THEN
      FUNVAL(ICUR) = 0.0
      BHFF HISTORY(LOOP) = MINBHF - BHFINITIAL(LOOP)
   ENDIF
325   CONTINUE
350   CONTINUE
C
C   ENDF
C
C   TIMESTEP = TIMESTEP + 1
C
C   RETURN
END
APPENDIX E

INSTRUCTIONS FOR STRESS BASED ADAPTIVE SIMULATION

At each time step, this algorithm attempts to maintain the maximum equivalent stress in the part at some specified stress profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which maximizes the stretch in the part while eliminating fracture and minimizing wrinkling. The equivalent stress will be calculated from Hill’s plane stress anisotropic quadratic yield function (Wagoner, 1997).

\[
\bar{\sigma}^2 = \frac{1}{r_{90}(r_0 + 1)} \left[ r_{90} \sigma_x^2 + r_0 \sigma_y^2 + r_0 r_{90} (\sigma_x - \sigma_y)^2 + \left(2r_{45} + 1\right)(r_0 + r_{90}) \tau_{xy}^2 \right]
\]

(Equation 4.25)

This algorithm allows the user to specify:

- \(k_p, k_i, k_d\) controller constants
- static average filtering window size
- minimum and maximum BHF
- start time for control or automatic start
- any constant level stress profile and ramp time
- bulk search of maximum stress or target zone or target element

The optimal controller and filtering constants have been iteratively determined to maximize robustness. They are as follows:

\[
\begin{align*}
KP &= 20 \\
KI &= 0.0 \\
KD &= 0.0
\end{align*}
\]
\[ N_{TH} = 250 \]

The maximum and minimum BHF are dictated by press and tooling limits. It is recommended that the initial BHF should be set relatively high near the fracture limit to minimize the amount of time it takes the stress reach the setpoint. The algorithm will quickly modify the BHF from this point on to ensure no splitting. This high initial BHF tends to improve control stability.

The start time should be set when the process is well established typically after 5-10% of the draw depth is achieved. There is also an option for the control to begin automatically when the measured stress becomes greater than or equal than the setpoint stress. This option improves control stability and is recommended as an initial starting point for investigations. To use automatic start, just enter a negative value for the STARTIME.

Any constant level stress profile may be specified and this setpoint can be ramped in at any slope to improve controllability. It is recommended that the stress setpoint be set at the average of the yield and ultimate tensile strength of the material to maximize stretch while avoiding splitting. The setpoint should be ramped in over a short period of about 5-10% of the draw depth.

The entire sheet or zone may be defined whereby the algorithm searches for the maximum stress. The zone option forces the algorithm to only analyze the region in which fracture is likely to occur to minimize false readings. Another option is to specify a specific element in which failure is likely to occur. It is recommended that a target element be chosen rather than the entire part or a zone to improve stability.

The following user specified variables are defined for this control algorithm:

STRESSLIMIT: User specified stress setpoint target.
RAMPTIME: User specified timestep value for ramping in of the stress setpoint. The
   RAMPTIME should be less than ENDTIME and greater than STARTTIME.

ELEMENT: User specified external element number for stress measurement.

The following calculated variables are defined for this control algorithm:

IELEM: Internal element number of ELEMENT.

STRESSMAX: Current Hill’s equivalent stress for ELEMENT.

AVGSTRESSMAX: Current summated STRESSMAX value to be used for the static
   averaging window and is reset everytime the static averaging window is renewed.

STRESSINITIAL: Equivalent stress value of ELEMENT at TIMESTEP=STARTTIME. 
   This is used to calculate the ramping of the stress setpoint.

STRESSRAMP: Current stress setpoint with ramping calculation. The STRESSRAMP
   begins at STARTTIME or automatic start and takes on the value of the current
   STRESSMAX. The STRESSRAMP then ramps up to the STRESSLIMIT value
   by RAMPTIME. The STRESSRAMP is equivalent to STRESSLIMIT thereafter.

STRESSPREV: Value of STRESSMAX during the previous static averaging window.

The configuration file "control.prm" takes the following format:

# Control Parameter file. The first line contains
# KF, KI, KD, STRESSLIMIT, MINBHF, MAXBHF, ELEMENT, N_TH in (4F10.5, 2F10.1, 2I10)
#2345678901234567890123456789012345678901234567890123456789012345678901234567890
# 0.00000  0.00000  0.00000  0.30000  0.0  200.0  505  250
#
# Extra Parameters
# STARTTIME, RAMPTIME, ENDTIME (3F10.1)
#2345678901234567890123456789012345678901234567890123456789012345678901234567890
# 2750  12500  51500
#
# This is the name of the output file, up to 40 characters
pie12-e3.log

Please note that the format and positions of the numbers are precise and are indicated in
the commented areas. These number formats are standard Fortran number formats. For
example, a format "3F10.5" indicates that there are 3 floating point numbers which are 10
characters long (including decimal and sign) which have five digits after the decimal
place. The format "5I10" indicates that there are five integers with 10 characters each (including decimal and sign).

The output *.LOG file takes the following format:

```
<table>
<thead>
<tr>
<th>KP</th>
<th>KI</th>
<th>KD</th>
<th>STRESSLI</th>
<th>20</th>
<th>0</th>
<th>0</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINBHF</td>
<td>MAXBHF</td>
<td>ELEMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STARTTIM</td>
<td>RAMPTIM</td>
<td>ENDTIM</td>
<td>N_TH:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIMESTEF</td>
<td>TIME</td>
<td>ERROR</td>
<td>SUMERRSLOPE</td>
<td>DELTABH</td>
<td>BHFHIST</td>
<td>STRESSR</td>
<td>STRESSM</td>
</tr>
<tr>
<td>2869</td>
<td>1.09594</td>
<td>-0.00213</td>
<td>-0.00213</td>
<td>0.1708</td>
<td>-0.04251</td>
<td>-0.04251</td>
<td>0.17026</td>
</tr>
<tr>
<td>3119</td>
<td>1.19214</td>
<td>-0.00474</td>
<td>-0.00686</td>
<td>0.00581</td>
<td>-0.09474</td>
<td>-0.13725</td>
<td>0.17346</td>
</tr>
<tr>
<td>3369</td>
<td>1.28847</td>
<td>-0.01299</td>
<td>-0.01965</td>
<td>0.01145</td>
<td>-0.25977</td>
<td>-0.39702</td>
<td>0.17666</td>
</tr>
<tr>
<td>3619</td>
<td>1.38491</td>
<td>-0.01112</td>
<td>-0.03097</td>
<td>0.00134</td>
<td>-0.22246</td>
<td>-0.61948</td>
<td>0.17986</td>
</tr>
<tr>
<td>3869</td>
<td>1.48153</td>
<td>-0.01692</td>
<td>-0.04789</td>
<td>0.009</td>
<td>-0.33837</td>
<td>-0.95785</td>
<td>0.18307</td>
</tr>
<tr>
<td>4119</td>
<td>1.5783</td>
<td>-0.02084</td>
<td>-0.08873</td>
<td>0.00714</td>
<td>-0.41684</td>
<td>-1.37469</td>
<td>0.18629</td>
</tr>
<tr>
<td>4369</td>
<td>1.67521</td>
<td>-0.02078</td>
<td>-0.08952</td>
<td>0.00316</td>
<td>-0.41562</td>
<td>-1.79031</td>
<td>0.18951</td>
</tr>
<tr>
<td>4619</td>
<td>1.77234</td>
<td>-0.02169</td>
<td>-0.1121</td>
<td>0.00414</td>
<td>-0.43384</td>
<td>-2.22415</td>
<td>0.19274</td>
</tr>
<tr>
<td>4869</td>
<td>1.86966</td>
<td>-0.02562</td>
<td>-0.13682</td>
<td>0.00715</td>
<td>-0.5123</td>
<td>-2.73645</td>
<td>0.19597</td>
</tr>
<tr>
<td>5119</td>
<td>1.96719</td>
<td>-0.02814</td>
<td>-0.16496</td>
<td>0.00576</td>
<td>-0.56271</td>
<td>-3.29917</td>
<td>0.19921</td>
</tr>
<tr>
<td>5369</td>
<td>2.06494</td>
<td>-0.03173</td>
<td>-0.19669</td>
<td>0.00684</td>
<td>-0.63455</td>
<td>-3.93372</td>
<td>0.20246</td>
</tr>
<tr>
<td>5619</td>
<td>2.16293</td>
<td>-0.03772</td>
<td>-0.23441</td>
<td>0.00925</td>
<td>-0.75449</td>
<td>-4.6882</td>
<td>0.20572</td>
</tr>
<tr>
<td>5869</td>
<td>2.26108</td>
<td>-0.03904</td>
<td>-0.27345</td>
<td>0.00458</td>
<td>-0.78088</td>
<td>-5.46908</td>
<td>0.20898</td>
</tr>
<tr>
<td>6119</td>
<td>2.35937</td>
<td>-0.03894</td>
<td>-0.31239</td>
<td>0.00316</td>
<td>-0.77872</td>
<td>-6.24781</td>
<td>0.21225</td>
</tr>
<tr>
<td>6369</td>
<td>2.45786</td>
<td>-0.04277</td>
<td>-0.35516</td>
<td>0.00711</td>
<td>-0.85543</td>
<td>-7.10324</td>
<td>0.21552</td>
</tr>
<tr>
<td>6619</td>
<td>2.55666</td>
<td>-0.04552</td>
<td>-0.40068</td>
<td>0.00602</td>
<td>-0.91035</td>
<td>-8.01359</td>
<td>0.2188</td>
</tr>
<tr>
<td>6869</td>
<td>2.65579</td>
<td>-0.04748</td>
<td>-0.44816</td>
<td>0.00526</td>
<td>-0.9497</td>
<td>-8.95329</td>
<td>0.2221</td>
</tr>
<tr>
<td>7119</td>
<td>2.75509</td>
<td>-0.0428</td>
<td>-0.49097</td>
<td>0.00139</td>
<td>-0.85606</td>
<td>-9.81934</td>
<td>0.2254</td>
</tr>
</tbody>
</table>
```

The user may make a plot of TIME versus STRESSRAMP, STRESSMAX, and PAMBHF to see the control action visually. It is best to format the graph so that STRESSRAMP and STRESSMAX are on one axis scale while PAMBHF is on another.

There are two other variations of the stress based algorithm that may prove potentially useful. The first looks for the maximum stress in the entire part rather than just in a particular element. The second looks for the maximum stress in a particular user defined "ZONE". Each of the variations are contained in the following directories of the author's files:
DIRECTORY  ALGORITHM
Element      User defined element number for stress calculation
Stress       Maximum stress throughout entire part
Zone         Maximum stress throughout user defined zone

The "ZONE" concept is useful for pure deep drawing and is illustrated in Figure E.1. Basically the user designates a ZONE size that begins at the bottom of the cup and stretches upwards. This ZONE moves with the bottom of the cup as deep drawing commences. Basically, the ZONE should contain the region of the cup which is likely to fracture.

ZONE: Moving window size for maximum stress search.

![Figure E.1: Definition of "Zone" for stress algorithm](image)

The user subroutine for the stress based algorithm is included below. Remember to append the GETNXTLN subroutine from Appendix C.
C Stress Based User Subroutine

SUBROUTINE LDCMOD(NUMNOD, LABNOD, DXYZ, DISP, VEL, ACC, NUMSHE, 
                   . LABSHE, KONSHE, INDEX, STRTAB, NUMCUR, LABCUR, 
                   . FUNVAL, MATTYP, CCM, NNPROP, INOD, ISHEL, IMAT, 
                   . TIME, NUMCON, CONFORCE)

C
REAL LSIG11, LSIG22, LSIG12, MSIG11, MSIG12, MSIG22, KMOD1, KMOD2, 
     . MEPSPL, LEPS11, LEPS22, LEPS12, DXYZ, DISP, VEL, ACC, CCM, G, F, N, H
COMMON/AUX40/S1(48), S2(48), S3(48)
DIMENSION LABNOD(*), DXYZ(3,*), LABSHE(*), KONSHE(6,*), INDEX(*), 
                  . DISP(3,*), VEL(3,*), ACC(3,*), STRTAB(*), LABCUR(*), 
                  . FUNVAL(*), MATTYP(*), CCM(NNPROP,*), ISHEL(*), INOD(*), 
                  . IMAT(*), CONFORCE(5,*)

C
C Control Parameters
C
REAL KP, KI, KD, STRESSLIMIT, MINBHF, MAXBHF
INTEGER N_TH, ELEMENT, TIMESTEP, NTMS
INTEGER STARTIME, RAMPTIME, ENDTIME
REAL DELTABHF, BHFISTORY, PAMBHF, BFINITIAL
REAL STRESSMAX, STRESSINITIAL, STRESSRAMP, AVGSTRESSMAX
REAL STRESSPREV, ERROR, SUMERROR, AVGERR, SLOPE
LOGICAL FIRST_TIME, EOF, BEGIN
INTEGER LUNPRM, LOG, IOS, NCHR, IELEM
CHARACTER*40 FILE_NAME
CHARACTER*80 LINE

C
DATA KP, KI, KD/ 0.0, 0.0, 0.0, 0.0/, STRESSLIMIT/ 0.0/
DATA MINBHF / 0.0/, MAXBHF/ 0.0/, ELEMENT/ 0/, IELEM/ 0/
DATA STARTIME/ 0/, RAMPTIME/ 0/, ENDTIME/ 0/, N_TH/ 0/
DATA TIMESTEP/ 1/, NTMS/ 0/, DELTABHF/ 0.0/, BHFISTORY/ 0.0/
DATA PAMBHF/ 0.0/, BFINITIAL/ 0.0/, STRESSMAX/ 0.0/
DATA STRESSINITIAL/ 0.0/, STRESSRAMP/ 0.0/, AVGSTRESSMAX/ 0.0/
DATA STRESSPREV/ 0.0/, ERROR/ 0.0/, SUMERROR/ 0.0/
DATA AVGERR/ 0.0/, SLOPE/ 0.0/, BEGIN/.FALSE./
DATA FILE_NAME/'' '', LUNPRM/ 77/, LOG/ 78/, FIRST_TIME/.TRUE./

C
C Find the stress of the user specified element and vary the BHF
C with a PID controller to match this stress with a user specified
C stress setpoint to avoid splitting, minimize wrinkling, and maximize
C final part stretch.
C
C Read input values from "control.prm".
C
IF ( FIRST_TIME ) THEN
  OPEN ( LUNPRM, FILE='control.prm', IOSTAT=IOS )
  IF ( IOS .NE. 0 ) THEN
    WRITE ( *, 5 )
    FORMAT( 'Could not open control.prm' )
    STOP
  ENDIF

CALL getnxtln ( LUNPRM, '#', LINE, EOF )
READ (LINE,10) KP,KI,KD,STRESSLIMIT,MINBHF,MAXBHF,ELEMENT,N_TH
10 FORMAT( 4F10.5, 2F10.1, 2I10 )

216
CALL getnxtln ( LUNPRM, '#', LINE, EOF )
READ ( LINE, 15 ) STARTIME, RAMPTIME, ENDTIME
FORMAT ( 3I10 )
C
C Get the name of the output/log file
C
CALL getnxtln ( LUNPRM, '#', LINE, EOF )
NCHR = LLLEN ( LINE )
FILE_NAME = LINE (1:NCHR) // CHAR(0)
C
CLOSE ( LUNPRM )
NTMS = 0
AVGERR = 0.0
FIRST_TIME = .FALSE.
C
C Find Internal Element Number
C
DO 100 ISHE=1, NUMSHE
   IF ( ISHEL(ISHE) .EQ. ELEMENT ) IELEM = ISHE
   CONTINUE
100
C
C Open the log file
C
OPEN ( LOG, FILE=FILE_NAME, IOSTAT=IOS )
C
WRITE ( LOG, 20 ) KP, KI, KD, STRESSLIMIT
20 FORMAT ( 'KP,KI,KD,STRESSLIMIT:', 4F10.5 )
WRITE ( LOG, 25 ) MINBHF, MAXBHF, ELEMENT, IELEM
25 FORMAT ( 'MINBHF, MAXBHF, ELEMENT, IELEM: ', 2F10.1, 2I10 )
WRITE ( LOG, 30 ) STARTIME, RAMPTIME, ENDTIME, N_TH
30 FORMAT ( 'STARTIME, RAMPTIME, ENDTIME, N_TH:', A4I10)
WRITE ( LOG, 35 )
35 FORMAT ( 'TIMESTEP,TIME,ERROR,SUMERROR,SLOPE,DELTABHF,','
   * 'BHFHISTORY,STRESSRAMP,STRESSMAX,PAMBHF' )
ENDIF
C
C Initialization of STRESSMAX
C
STRESSLIMIT = 250
STRESSMAX = -1.0
NBSHEMX = 0
C
C******************************************************************************
C Get element values of element number NSHESL
C******************************************************************************
C
ISHE=IELEM
C
DO 200 ISHE=1, NUMSHE
   NSHE = LABSHE(ISHE)
   IF (NSHE.EQ.NSHESL) THEN
C Define variables relative to element NSHE
C
   IGAUS = 0         ! Integration type flag
   IN = INDEX ( ISHE ) - 1 ! Address of NSHE in INDEX table
   IP = KONSHE(6, ISHE) ! Number of through thickness int. points
C
C Extract thickness and thinning values
C
217
IF(IGAUS.EQ.1) THEN  ! Selective integration (Hughes-Tezrd.)
ISTEP = 6
ISFIX = 22
IADD = 4
C
TH0 = STRTAB(IN+21)  ! Initial thickness
C
THK = STRTAB(IN+1)  ! Current thickness
C
THN = (TH0-THK)/TH0  ! Thinning ratio
ELSE
ISTEP = 6
ISFIX = 18
IADD = 4
C
TH0 = STRTAB(IN+17)  ! Initial thickness
C
THK = STRTAB(IN+1)  ! Current thickness
C
THN = (TH0-THK)/TH0  ! Thinning ratio
ENDIF
C
C Get stresses at each integration point
C
DO 210 I=1,IP
   K = IN + ISFIX + (I-1)*ISTEP
   S1(I) = STRTAB(K+1)  ! Sigma 11
   S2(I) = STRTAB(K+2)  ! Sigma 22
   S3(I) = STRTAB(K+3)  ! Sigma 12
210 CONTINUE
C
C Get Lower/Upper surface stress tensor
C
LSIG11 = S1(1)
C
LSIG22 = S2(1)
C
LSIG12 = S3(1)
C
USIG11 = S1(IP)
C
USIG22 = S2(IP)
C
USIG12 = S3(IP)
C
C Get Middle surface stress tensor
C
IS1 = (IP+1)/2
IS2 = IP/2 + 1
MSIG11 = 0.5*(S1(IS1) + S1(IS2))
MSIG22 = 0.5*(S2(IS1) + S2(IS2))
MSIG12 = 0.5*(S3(IS1) + S3(IS2))
C
C Get Middle surface plastic strain
C
KMID1 = IN + ISFIX + (IS1-1)*ISTEP + IADD
C
KMID2 = IN + ISFIX + (IS2-1)*ISTEP + IADD
C
MEPSPL = 0.5*(STRTAB(KMID1)+STRTAB(KMID2))
C
C Get Lower/Upper surface strain tensor
C
K = IN + ISFIX - 8
C
LEPS11 = STRTAB(K+4)  ! Epsilon 11 Lower surface
C
LEPS22 = STRTAB(K+5)  ! Epsilon 22 Lower surface
C
LEPS12 = 0.5*STRTAB(K+6)  ! Epsilon 12 Lower surface
C
UEPS11 = STRTAB(K+1)  ! Epsilon 11 Upper surface
C
UEPS22 = STRTAB(K+2)  ! Epsilon 22 Upper surface
C
UEPS12 = 0.5*STRTAB(K+3)  ! Epsilon 12 Upper surface
C
ENDIF
C
C Compute Equivalent Stress (Hill)
C
218
IF ((MATTYP(KONSHE(1,ISHE)) .EQ. 107) .OR. 
   (MATTYP(KONSHE(1,ISHE)) .EQ. 109)) THEN
  G = CCM(68, KONSHE(1,ISHE))
  F = CCM(69, KONSHE(1,ISHE))
  N = CCM(70, KONSHE(1,ISHE))
  H = 2 - G
  STRESSAUX = 2 * N * MSIG12 ** 2 - 2 * H * MSIG11 * MSIG22
  STRESSAUX = STRESSAUX + (G + H) * MSIG11 ** 2
  STRESSAUX = STRESSAUX + (F + H) * MSIG22 ** 2
  STRESSAUX = SQRT (STRESSAUX * 0.5)
  STRESSEQ = STRESSAUX

Check if the element is in the wall of the part

  NODE1 = KONSHE(2,ISHE)
  NODE2 = KONSHE(3,ISHE)
  NODE3 = KONSHE(4,ISHE)
  NODE4 = KONSHE(5,ISHE)

  ZNODE1 = DXYZ(3,NODE1)
  ZNODE2 = DXYZ(3,NODE2)
  ZNODE3 = DXYZ(3,NODE3)

  IF (NODE4 .NE. 0) THEN
    ZNODE4 = DXYZ(3,NODE4)
  ELSE
    ZNODE4 = DEPTH
  ENDIF

  IF (Timesteps .GT. STARTIME) THEN
    ZONEPOS = (DEPTH/ENDTIME*Timesteps) - ZONE
    IF (ZONEPOS .LT. 0.0) ZONEPOS = 0.0
    IF (ZONEPOS .GT. (DEPTH-ZONE)) ZONEPOS = DEPTH - ZONE
    IF ( (ZNODE1 .GT. ZONEPOS) .AND. (ZNODE2 .GT. ZONEPOS) .AND. 
        (ZNODE3 .GT. ZONEPOS) .AND. (ZNODE4 .GT. ZONEPOS) ) THEN
      STRESSMAX = STRESSEQ
      NBSHEMAX = ISHE
    ENDIF
  ELSE
    IF (STRESSEQ .GT. STRESSMAX) THEN
      STRESSMAX = STRESSEQ
      NBSHEMAX = ISHE
    ENDIF
  ENDIF

ENDIF

Calculate Equivalent Stress of ELEMENT

  IF (ISHEL(ISHE) .EQ. ELEMENT) THEN
    G = CCM(68, KONSHE(1,ISHE))
    F = CCM(69, KONSHE(1,ISHE))
    N = CCM(70, KONSHE(1,ISHE))
    H = 2 - G
    STRESSAUX = 2 * N * MSIG12 ** 2 - 2 * H * MSIG11 * MSIG22
    STRESSAUX = STRESSAUX + (G + H) * MSIG11 ** 2
    STRESSAUX = STRESSAUX + (F + H) * MSIG22 ** 2
    STRESSAUX = SQRT (STRESSAUX * 0.5)
    STRESSEQ = STRESSAUX
    STRESSMAX = STRESSEQ

219
ENDIF

C Calculated Major Stress of ELEMENT
C IF (ISHE .EQ. IELEM) THEN
C MSIG1 = ((MSIG11+MSIG22)/2)
C MSIG1 = MSIG1 + SQRT (((MSIG11-MSIG22)/2)**2+MSIG12**2)
C MSIG2 = MSIG1 - SQRT (((MSIG11-MSIG22)/2)**2+MSIG12**2)
C ENDIF
C
C 200 CONTINUE
C
C******************************************************************************
C Get displacement of all nodes of element NBSHEMAX
C******************************************************************************
C
C NODE1 = KONSHE(2,NBSHEMAX)
C NODE2 = KONSHE(3,NBSHEMAX)
C NODE3 = KONSHE(4,NBSHEMAX)
C NODE4 = KONSHE(5,NBSHEMAX)
C NDOF = 6
C XNODE1 = DXYZ(1,NODE1)
C YNODE1 = DXYZ(2,NODE1)
C ZNODE1 = DXYZ(3,NODE1)
C XNODE2 = DXYZ(1,NODE2)
C YNODE2 = DXYZ(2,NODE2)
C ZNODE2 = DXYZ(3,NODE2)
C XNODE3 = DXYZ(1,NODE3)
C YNODE3 = DXYZ(2,NODE3)
C ZNODE3 = DXYZ(3,NODE3)
C IF (NODE4 .NE. 0) THEN
C XNODE4 = DXYZ(1,NODE4)
C YNODE4 = DXYZ(2,NODE4)
C ZNODE4 = DXYZ(3,NODE4)
C XCOG = (XNODE1 + XNODE2 + XNODE3 + XNODE4) / 4
C YCOG = (YNODE1 + YNODE2 + YNODE3 + YNODE4) / 4
C ZCOG = (ZNODE1 + ZNODE2 + ZNODE3 + ZNODE4) / 4
C ELSE
C XCOG = (XNODE1 + XNODE2 + XNODE3) / 3
C YCOG = (YNODE1 + YNODE2 + YNODE3) / 3
C ZCOG = (ZNODE1 + ZNODE2 + ZNODE3) / 3
C ENDIF
C
C******************************************************************************
C Proportional, Integral, Derivative Controller
C******************************************************************************
C
C Check to see if it is time to begin control.
C
C Find the error (proportional), sum of previous errors (integral), and
C slope (derivative)
C
C IF (STARTTIME .LT. 0) THEN
    IF (STRESSMAX .GE. STRESSLIMIT) BEGIN=.TRUE.
    ELSE
    IF (Timestep .GT. STARTTIME) BEGIN=.TRUE.
    ENDIF
C
C IF (BEGIN) THEN
    IF ((Timestep.LT.RAMPTIME) .AND. (STARTTIME .GE. 0)) THEN
        STRESSRAMP = STRESSINITIAL + (STRESSLIMIT - STRESSINITIAL)
* (RAMPTIME - STARTIME) * (TIMESTEP - STARTIME)
ELSE
  STRESSRAMP = STRESSLIMIT
ENDIF
ERROR = STRESSRAMP - STRESSMAX

C Average N_TH steps before attempting control action

C
AVGERR = AVGERR + ERROR
AVGSTRESSMAX = AVGSTRESSMAX + STRESSMAX
NTMS = NTMS + 1

C
IF ( NTMS .GE. N_TH ) THEN
  ERROR = AVGERR/NTMS
  STRESSMAX = AVGSTRESSMAX/NTMS
  NTMS = 0
  AVGERR = 0.0
  AVGSTRESSMAX = 0.0

C
SUMERROR = SUMERROR + ERROR
SLOPE = STRESSMAX - STRESSPREV
STRESSPREV = STRESSMAX

C
Now calculate the binder load adjustment DELTABHF. This is calculated by summing the proportional, integral, and derivative values by their proportionality constants and then dividing by STRESSLIMIT to obtain a unitless value.

C
DELTABHF = KP*ERROR + KI*SUMERROR + KD*SLOPE
BHFHISTORY = BHFHISTORY + DELTABHF

C
Adjust the binder load curve #2 by DELTABHF.

C
NCURSL = 2
DO 400 ICUR=1,NUMCUR
  NCUR = LABCUR(ICUR)
  IF (NCUR.EQ.NCURSL) THEN
    BFINITIAL=FUNVAL(ICUR)
    FUNVAL(ICUR) = BHFHISTORY+FUNVAL(ICUR)
    IF (FUNVAL(ICUR) .LT. MINBHF) THEN
      FUNVAL(ICUR) = MINBHF
      BHFHISTORY = MINBHF - BFINITIAL
    ENDIF
    IF (FUNVAL(ICUR) .GT. MAXBHF) THEN
      FUNVAL(ICUR) = MAXBHF
      BHFHISTORY = MAXBHF - BFINITIAL
    ENDIF
    PAMBHF = FUNVAL(ICUR)
  ENDIF
400 CONTINUE

C
Output values to log file

C
  WRITE ( LOG, 450 ) TIMESTEP, TIME, ERROR, SUMERROR, SLOPE,
  * DELTABHF, BHFHISTORY, STRESSRAMP, STRESSMAX, PAMBHF
450 FORMAT( 110, 9(1h,F10.5) )

C
ENDIF

C
Adjust the binder load curve #2 by DELTABHF again.

C
221
NCURSL = 2
DO 500 ICUR=1,NUMCUR
   NCUR = LABCUR(ICUR)
   IF (NCUR.EQ.NCURSL) THEN
      FUNVAL(ICUR) = BHPHISTORY+FUNVAL(ICUR)
   ENDIF
500   CONTINUE
C
ELSE
   STRESSINITIAL = STRESSMAX
ENDIF
C
TIMESTEP = TIMESTEP + 1
C
RETURN
END
APPENDIX F

INSTRUCTIONS FOR STRAIN BASED ADAPTIVE SIMULATION

At each time step, this algorithm attempts to maintain the maximum thinning in the part at some specified thinning profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which eliminates fracture in the part and minimizes wrinkling. The maximum thinning is defined as:

$$\text{maximum thinning} = \frac{t_0 - t_{\text{min}}}{t_0}$$  \hspace{1cm} \text{(Equation 4.26)}$$

Where \( t_{\text{min}} \) is the minimum thickness in the part.

This algorithm allows the user to specify:
- \( k_p, k_i, k_d \) controller constants
- static average filtering window size
- minimum and maximum BHF
- start time for control
- any time rate of thinning

The optimal controller and filtering constants have been iteratively determined to maximize robustness. They are as follows:

\[ \text{KP} = 3 \]
\[ \text{KI} = 0 \]
\[ \text{KD} = 0 \]
\[ \text{N\_TH} = 100 \]
The maximum and minimum BHF are dictated by press and tooling limits. The start time should be set soon after deep drawing has begun typically after 2-3% of the draw depth has been achieved. Any time rate of thinning may be specified. It is recommended that the thinning vary from 0% at the beginning of the process to around 30% by the end of the process to maximize stretch while avoiding splitting.

The following user specified variables are defined for this control algorithm:

THINLIMIT: User specified thinning setpoint target.

The following calculated variables are defined for this control algorithm:

THINMAX: Value of the maximum thinning in the sheet.

NBSHEMAX: Internal element number of the current maximum thinning.

AVGTHINMAX: Current summated THINMAX to be used in the static averaging windows and is reset everytime the static averaging window is renewed.

THINPREV: Thinning value from the previous static averaging window.

THINRAMP: Current thinning setpoint value calculated from the line drawn from the point (0,STARTTIME) to the point (THINLIMIT,ENDTIME).

AVGTHINRAMP: Current summated THINRAMP to be used in the static averaging windows and is reset everytime the static averaging window is renewed.

The configuration file "control.prm" takes the following format:

```
# Control Parameter file. The first line contains
# KP, KI, KD, THINLIMIT, MINBHF, MAXBHF, N_TH in (4F10.5, 2F10.1, I10)
#234567890123456789012345678901234567890123456789012345678901234567890
3.00000 0.00000 0.00000 0.17500 0.0 200.0 100
#
# Extra Parameters
# STARTTIME, ENDTIME (2I10)
#234567890123456789012345678901234567890123456789012345678901234567890
500 20000
#
# This is the name of the output file, up to 40 characters
pie12-t11.log
```
Please note that the format and positions of the numbers are precise and are indicated in the commented areas. These number formats are standard Fortran number formats. For example, a format "3F10.5" indicates that there are 3 floating point numbers which are 10 characters long (including decimal and sign) which have five digits after the decimal place. The format "5I10" indicates that there are five integers with 10 characters each (including decimal and sign).

The output *.LOG file takes the following format:

<table>
<thead>
<tr>
<th>KP</th>
<th>KI</th>
<th>KD:</th>
<th>3</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>THINLIMIT</td>
<td>MINBH:</td>
<td>0.175</td>
<td>0</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>STARTTIME</td>
<td>ENDTIME</td>
<td>N_TH:</td>
<td>500</td>
<td>20000</td>
<td>100</td>
</tr>
<tr>
<td>TIMES</td>
<td>TIME</td>
<td>ERROR</td>
<td>SUMERR</td>
<td>SLOPE</td>
<td>DELTABH</td>
</tr>
<tr>
<td>600</td>
<td>0.22833</td>
<td>0.00377</td>
<td>0.00377</td>
<td>0.00105</td>
<td>0.0113</td>
</tr>
<tr>
<td>700</td>
<td>0.26645</td>
<td>0.00415</td>
<td>0.00792</td>
<td>0.00049</td>
<td>0.01246</td>
</tr>
<tr>
<td>800</td>
<td>0.30458</td>
<td>0.00454</td>
<td>0.01247</td>
<td>0.00049</td>
<td>0.01363</td>
</tr>
<tr>
<td>900</td>
<td>0.3427</td>
<td>0.00515</td>
<td>0.01762</td>
<td>0.00027</td>
<td>0.01546</td>
</tr>
<tr>
<td>1000</td>
<td>0.38083</td>
<td>0.0024</td>
<td>0.02002</td>
<td>0.00363</td>
<td>0.0072</td>
</tr>
<tr>
<td>1100</td>
<td>0.41895</td>
<td>0.00218</td>
<td>0.02221</td>
<td>0.00109</td>
<td>0.00655</td>
</tr>
<tr>
<td>1200</td>
<td>0.45709</td>
<td>0.00306</td>
<td>0.02527</td>
<td>0</td>
<td>0.00918</td>
</tr>
<tr>
<td>1300</td>
<td>0.49522</td>
<td>0.00408</td>
<td>0.02935</td>
<td>-0.00015</td>
<td>0.01225</td>
</tr>
<tr>
<td>1400</td>
<td>0.53338</td>
<td>0.00507</td>
<td>0.03442</td>
<td>-0.00011</td>
<td>0.01522</td>
</tr>
<tr>
<td>1500</td>
<td>0.57155</td>
<td>0.00608</td>
<td>0.0405</td>
<td>-0.00013</td>
<td>0.01824</td>
</tr>
<tr>
<td>1600</td>
<td>0.60974</td>
<td>0.00692</td>
<td>0.04742</td>
<td>0.00003</td>
<td>0.02076</td>
</tr>
<tr>
<td>1700</td>
<td>0.64793</td>
<td>0.00783</td>
<td>0.05472</td>
<td>0.00049</td>
<td>0.0219</td>
</tr>
<tr>
<td>1800</td>
<td>0.68614</td>
<td>0.00883</td>
<td>0.06155</td>
<td>0.00135</td>
<td>0.02408</td>
</tr>
<tr>
<td>1900</td>
<td>0.72437</td>
<td>0.00983</td>
<td>0.06875</td>
<td>0.0014</td>
<td>0.0189</td>
</tr>
<tr>
<td>2000</td>
<td>0.76262</td>
<td>0.00579</td>
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</table>

The user may make a plot of TIME versus THINRAMP, THINMAX, and PAMBHF to see the control action visually. It is best to format the graph so that THINRAMP and THINMAX are on one axis scale while PAMBHF is on another.
The user subroutine for the thinning based algorithm is included below. The user may find these files in the directory "Thin" in the author's files. Do not forget to append the GETNXTLN subroutine from Appendix C.

C**********************************************************************
C Thinning Based User Subroutine
C**********************************************************************
SUBROUTINE LDCMOD( NUMMOD, LABMOD, DXYZ, DISP, VEL, ACC, NMSHE, 
    LABSHE, KONSHE, INDEX, STRTAB, NUMCUR, LABCUR, 
    FUNVAL, MATTYP, CCM, NNPROP, INOD, ISHEL, IMAT, 
    IMAT(*), CONFORCE)

C REAL LSIG11, LSIG22, LSIG12, MSIG11, MSIG22, MSIG12, KMS1, KMS2, 
    MEPSPL, LEPS11, LEPS22, LEPS12, DXYZ, DISP, VEL, ACC, CCM, G, F, N, H
COMMON/AUX40/ S1(48), S2(48), S3(48)
DIMENSION LABMOD(*), DXYZ(*), LABSHE(*), KONSHE(6,*), INDEX(*), 
    DISP(*), VEL(*), ACC(*), STRTAB(*), LABCUR(*), 
    FUNVAL(*), MATTYP(*), CCM(3), INOD(*), 
    IMAT(*), CONFORCE(5,*),

C**********************************************************************
C Control Parameters
C**********************************************************************
REAL KP, KI, KD, THINLIMIT, DEPTH, MINBHF, MAXBHF
INTEGER N_TH, STARTTIME, ENDTIME, TIMESTEP, NTMS
REAL DELTABHF, BHFPART, PAMBHF, BHFINITIAL
REAL THINMAX, AVGTHINMAX, THINPREV, THINRAMP
REAL AVGTHINRAMP, ERROR, SUMERROR, SLOPE, THN
LOGICAL FIRST_TIME, EOF
INTEGER LUNPRM, LOG, IOS, NCHR
CHARACTER*40 FILE_NAME
CHARACTER*80 LINE

C DATA KP, KI, KD/ 0.0, 0.0, 0.0/, THINLIMIT/ 0.0/, DEPTH/ 0.0/
DATA MINBHF/ 0.0/, MAXBHF/ 0.0/, STARTTIME/ 0.0/, ENDTIME/ 0.0/
DATA N_TH/ 0.0/, TIMESTEP/ 1.0/, NTMS/ 0.0/, DELTABHF/ 0.0/, THINRAMP/ 0.0/
DATA BHFPART/ 0.0/, PAMBHF/ 0.0/, BHFINITIAL/ 0.0/
DATA THINMAX/ 0.0/, AVGTHINMAX/ 0.0/, THINPREV/ 0.0/, THN/ 0.0/
DATA AVGTHINRAMP/ 0.0/, ERROR/ 0.0/, SUMERROR/ 0.0/, SLOPE/ 0.0/
DATA FILE_NAME/ ' ', LUNPRM/ 77/, LOG/78/, FIRST_TIME/.TRUE./

C**********************************************************************
C Find the maximum thinning in the sheet and modify the BHF through a 
C PID controller to match the max thinning with a user specified 
C thinning setpoint target to avoid fracture, minimize wrinkling, and 
C maximum part stretch.
C
C Read input values from "control.prm"
C**********************************************************************
IF ( FIRST_TIME ) THEN
    OPEN ( LUNPRM, FILE='control.prm', IOSTAT=IOS )
    IF ( IOS .NE. 0 ) THEN
        WRITE ( *, 5 )
        FORMAT( 'Could not open control.prm' )
    END IF
ENDIF
STOP
ENDIF

CALL getnxml ( LUNPRM, '#', LINE, EOF )
READ ( LINE, 10 ) KP,KI,KD,THINLIMIT,MINBHF,MAXBHF,N_TH
10 FORMAT( 4F10.5, 2F10.1, I10 )
CALL getnxml ( LUNPRM, '#', LINE, EOF )
READ ( LINE, 15 ) STARTIME, ENDTIME
15 FORMAT( 2I10 )

C Get the name of the output/log file
C
CALL getnxml ( LUNPRM, '#', LINE, EOF )
NCHR = LLLEN ( LINE )
FILE_NAME = LINE(1:NCHR) // CHAR(0)

CLOSE ( LUNPRM )
NTMS = 0
FIRST_TIME = .FALSE.

C Open the log file
C
OPEN ( LOG, 20, FILE=FILE_NAME, IOSTAT=IOS )

WRITE ( LOG, 20 ) KP, KI, KD
20 FORMAT ( 'KP, KI, KD:' , 3F10.5 )
WRITE ( LOG, 25 ) THINLIMIT, MINBHF, MAXBHF
25 FORMAT ( 'THINLIMIT, MINBHF, MAXBHF:', F10.5, 2F10.1 )
WRITE ( LOG, 30 ) STARTIME, ENDTIME, N_TH
30 FORMAT ( 'STARTIME, ENDTIME, N_TH:', 3I10)
WRITE ( LOG, 35 )
35 FORMAT ( , 'TIMESTEP,TIME,ERROR,SUMERROR,SLOPE,DELTABHF,','
* 'BHFHISTORY,THINRAMP,THINMAX,PAMBHF' )
ENDIF

C Initialization of THINMAX
C
THINMAX = -1.0
NBSHEMAX = 0

C***************************************************************
C Find Maximum Thinning
C***************************************************************

DO 200 ISHE=1,NUMSHE
    IGAUS = 0 ! Integration type flag
    IN = INDEX ( ISHE ) - 1 ! Address of NSHE in INDEX table
    IP = KONSHE(6,ISHE) ! Number of through thickness int. points
C Extract thickness and thinning values
C
    IF ( IGAUS.EQ.1 ) THEN ! Selective integration (Hughes-
200 Tezd.)
        ISTEP = 6
        ISFIX = 22
        IADD = 4
        TH0 = STRTABI(IN+21) ! Initial thickness
        THK = STRTABI(IN+1) ! Current thickness
        THN = (TH0-THK)/TH0 ! Thinning ratio
    ENDIF
ELSE

    ISTEP = 6
    ISFIX = 18
    IADD = 4
    TH0 = STRTAB(IN+17)  ! Initial thickness
    THK = STRTAB(IN+1)   ! Current thickness
    THN = (TH0-THK)/TH0  ! Thinning ratio

ENDIF

C
C Find Maximum Thinning Value
C
    IF ((THN .GT. THINMAX) .AND. (THN .GE. 0.0) *
         .AND. (THN .LE. 1.0)) THEN
        THINMAX = THN
        NBSHEMAX = ISHE
    ENDIF

C
200 CONTINUE
C
C******************************************************************************
C Proportional, Integral, Derivative Controller
C******************************************************************************
C
C Check to see if it is time to begin control.
C
C Find the error (proportional), sum of previous errors (integral), and
C slope (derivative)
C
    IF (TSTEP .GT. STARTIME) THEN
        THINRAMP = THINLIMIT / ENDTIME * TSTEP
        IF (THINRAMP .GT. THINLIMIT) THINRAMP = THINLIMIT
    C
C Average N_TH steps before attempting control action
C
    AVGTHINRAMP = AVGTHINRAMP + THINRAMP
    AVGTHINMAX = AVGTHINMAX + THINMAX
    NTMS = NTMS + 1

C
    IF ( NTMS .GE. N_TH ) THEN
        THINRAMP = AVGTHINRAMP / NTMS
        THINMAX = AVGTHINMAX / NTMS
        NTMS = 0
        AVGTHINRAMP = 0.0
        AVGTHINMAX = 0.0

C
    ERROR = THINRAMP - THINMAX
    SUMERROR = SUMERROR + ERROR
    SLOPE = THINMAX - THINPREV
    THINPREV = THINMAX

C
C Now calculate the binder load adjustment DELTABHF. This is
C calculated by summing the proportional, integral, and derivative
C values by their proportionality constants and then dividing by
C STRESSLIMIT is obtain a unitless value.
C
    DELTABHF = KP*ERROR + KI*SUMERROR + KD*SLOPE
    BHPHISTORY = BHPHISTORY + DELTABHF

C
C Adjust the binder load curve #2 by DELTABHF.
C
228
NCURSL = 2
DO 400 ICUR = 1, NUMCUR
   NCUR = LABCUR(ICUR)
   IF (NCUR .EQ. NCURSL) THEN
      IF (TIMESTEP.EQ.(STARTIME+N_TH)) BFINITIAL=FUNVAL(ICUR)
      FUNVAL(ICUR) = BHFHISTORY + FUNVAL(ICUR)
      IF (FUNVAL(ICUR) .LT. MINBHF) THEN
         FUNVAL(ICUR) = MINBHF
         BHFHISTORY = MINBHF - BFINITIAL
      ENDIF
      IF (FUNVAL(ICUR) .GT. MAXBHF) THEN
         FUNVAL(ICUR) = MAXBHF
         BHFHISTORY = MAXBHF - BFINITIAL
      ENDIF
      PAMBHF = FUNVAL(ICUR)
   ENDIF
400    CONTINUE
C Output values to the log file
C
   WRITE (LOG,450) TIMESTEP,TIME,ERROR,SUMEROR,SLOPE,DELTABHF,
                  BHFHISTORY,THINRAMP,THINMAX,PAMBHF
450    FORMAT( I10, 10(1h,F10.5) )
C
ENDIF
C Adjust the binder load curve #2 by DELTABHF again.
C
   NCURSL = 2
   DO 500 ICUR = 1, NUMCUR
      NCUR = LABCUR(ICUR)
      IF (NCUR .EQ. NCURSL) THEN
         FUNVAL(ICUR) = BHFHISTORY + FUNVAL(ICUR)
      ENDIF
500    CONTINUE
C
ENDF
TIMESTEP = TIMESTEP + 1
C
RETURN
END
APPENDIX G

INSTRUCTIONS FOR FORCE BASED ADAPTIVE SIMULATION

At each time step, this algorithm attempts to maintain the punch force of the process at some specified force profile by actively varying the BHF using a PID controller. This strategy should produce a BHF profile which eliminates fracture and minimizes wrinkling in the part. This algorithm allows the user to specify:

- $k_p$, $k_i$, $k_d$ controller constants
- static average filtering window size
- minimum and maximum BHF
- start time for control or automatic start
- any constant level force profile

The optimal controller and filtering constants have been iteratively determined to maximize robustness. They are as follows:

\[
\begin{align*}
KP &= 2 \\
KI &= 0 \\
KD &= 0 \\
N_{TH} &= 250 \\
\end{align*}
\]

The maximum and minimum BHF are dictated by press and tooling limits. The initial value of the BHF should be set relatively high (near the fracture limit) in order to minimize the time it takes to reach the setpoint force. The controller will then modify the BHF to ensure that failure does not occur. Control stability is improved by setting the initial BHF high.
The start time should be set when the process is well established typically after 5-10% of the draw depth is achieved. There is also an option for the control to begin automatically when the measured punch force becomes greater than or equal to the setpoint force. This option improves control stability and is recommended as an initial starting point for investigations. To utilize the automatic start option just enter a negative value for STARTIME.

Any constant level of punch force may be specified. It is recommended that the punch force be set at 75% of the minimum punch force that causes fracture in constant level BHF trials. This should maximize final part stretch while avoiding splitting and minimizing wrinkling.

The following user specified variables are defined for this control algorithm:

FORCE: User specified punch force setpoint target.
PAIR: The external number of the punch/sheet contact interface boundary condition.

The following calculated variables are defined for this control algorithm:

PUNCH: The current value of the punch contact force.
AVGPUNCH: The current summated PUNCH value to be used in the static averaging window and resets every time the static averaging window is renewed.
PUNCHPREV: The value of the punch contact force during the previous static averaging window.

The configuration file "control.prm" takes the following format:

```plaintext
# Control Parameter file. The first line contains # KP, KI, KD, FORCE, MINEHF, MAXBHF, STARTIME, N_TH in (3F10.5, F10.3, 2F10.1, 2I10) #234567890123456789012345678901234567890123456789012345678901234567890 # 2.00000 0.00000 0.00000 10.0000 0.0 200.0 -1 250 # # Extra Parameters # PAIR in (I10)
```

231
Please note that the format and positions of the numbers are precise and are indicated in the commented areas. These number formats are standard Fortran number formats. For example, a format "3F10.5" indicates that there are 3 floating point numbers which are 10 characters long (including decimal and sign) which have five digits after the decimal place. The format "5I10" indicates that there are five integers with 10 characters each (including decimal and sign).

The output *.LOG file takes the following format:

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<th>KP</th>
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<th>KD:</th>
<th>FORCE</th>
<th>MINBHF</th>
<th>MAXBHF:</th>
<th>START/</th>
<th>MIN_TH</th>
<th>PAIR:</th>
<th>TIME</th>
<th>TIFEST</th>
<th>ERROR</th>
<th>SUMERR</th>
<th>SLOPE</th>
<th>DELTABH</th>
<th>BFHIST</th>
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<td>-35.95</td>
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<td>-5.23147</td>
<td>-50</td>
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<td>0</td>
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<td>-2.77624</td>
<td>-38.7252</td>
<td>0.16051</td>
<td>-5.55249</td>
<td>-50</td>
<td>12</td>
<td>14.77624</td>
</tr>
</tbody>
</table>

The user may make a plot of TIME versus FORCE, PUNCH, and PAMBHF to see the control action visually. It is best to format the graph so that FORCE and PUNCH are on one axis scale while PAMBHF is on another.
The user subroutine for the force based algorithm is included below. The user may find these files in the directory "Force" in the author's files. Please remember to append the GETNXTLN subroutine from Appendix C.

```fortran
C******************************************************************************
C Force Based User Subroutine
C******************************************************************************

SUBROUTINE LDCMOD(NUMMOD, LABNOD, DXYZ, DISP, VEL, ACC, NUMSHE,
                    LABSHE, KONSHE, INDEX, STRTAB, NUMCUR, LABCUR,
                    FUNVAL, MATTYP, CCM, NNP, INOD, ISHE, IMAT, TIME, NUMCON, CONFORCE)

REAL LSIG11, LSIG22, LSIG12, MSIG11, MSIG22, MSIG12, KMD1, KMD2,
       MEPSL, LEPS11, LEPS22, LEPS12, DXYZ, DISP, VEL, ACC, CCM, G, F, N, H
COMMON/AUX40/S1(48), S2(48), S3(48)
DIMENSION LABNOD(*), DXYZ(3,*), LABSHE(*), KONSHE(6,*), INDEX(*),
                    DISP(3,*), VEL(3,*), ACC(3,*), STRTAB(*), LABCUR(*),
                    FUNVAL(*), MATTYP(*), CCM(NNP, *), ISHE(*), IMAT(*),
                    CONFORCE(5,*)

C******************************************************************************
C Control Parameters
C******************************************************************************

REAL KP, Ki, KD, FORCE, MINBHF, MAXBHF
INTEGER STARTIME, N_TH, PAIR, TIMESTEP, NTMS
REAL DELTABHF, BHFHISTORY, PAMBHF, BHFINITIAL
REAL PUNCH, AVGPPUNCH, PNUMPREV
REAL ERROR, SUMERROR, SLOPE
LOGICAL FIRST_TIME, EOF, BEGIN
INTEGER LUNPRM, LOG, NCHR, IELEM
CHARACTER*40 FILE_NAME
CHARACTER*80 LINE

DATA KP, Ki, KD/ 0.0, 0.0, 0.0, 0.0/, FORCE/ 0.0/
DATA MINBHF / 0.0/, MAXBHF/ 0.0/, BEGIN/.FALSE./
DATA STARTIME/ 0/, N_TH/ 0/, PAIR / 0/
DATA TIMESTEP/ 1/, NTMS/ 0/, DELTABHF/ 0.0/, BHFHISTORY/ 0.0/
DATA PAMBHF/ 0.0/, BHFINITIAL/ 0.0/, PUNCH/ 0.0/, AVGPPUNCH/ 0.0/
DATA PNUMPREV/ 0.0/, ERROR/ 0.0/, SUMERROR/ 0.0/, SLOPE/ 0.0/
DATA FILE_NAME/' ', LUNPRM/ 77/, LOG/78/, FIRST_TIME/.TRUE./

C******************************************************************************
C Determine the punch contact force and modify the BHF through a PID
C controller to maintain the punch force at a user specified setpoint
C force to avoid splitting, minimize wrinkling, and maximize final
C part stretch.
C******************************************************************************

C Read input values from "control.prm"

C******************************************************************************

IF ( FIRST_TIME ) THEN
    OPEN ( LUNPRM, FILE='control.prm', IOSTAT=IOS )
    IF ( IOS .NE. 0 ) THEN
        WRITE ( *, 5 )
        FORMAT( 'Could not open control.prm' )
```
STOP
ENDIF

CALL getnxtn ( LUNPRM, '#', LINE, EOF )
READ (LINE,10) KP,KI,KD,FORCE,MINBHF,MAXBHF,STARTTIME,N_TH
10 FORMAT( 3F10.5, F10.3, 2F10.1, I10 )
CALL getnxtn ( LUNPRM, '#', LINE, EOF )
READ (LINE,15) PAIR
15 FORMAT( I10 )

C Get the name of the output/log file
C
CALL getnxtn ( LUNPRM, '#', LINE, EOF )
NCHR = LLEN ( LINE )
FILE_NAME = LINE(1:NCHR) // CHAR(0)

CLOSE ( LUNPRM )
NTMS = 0
FIRST_TIME = .FALSE.

C Open the log file
C
OPEN ( LOG, FILE=FILE_NAME, IOSTAT=IOS )

WRITE( LOG, 20 ) KP, KI, KD
20 FORMAT( 'KP,KI,KD: ', 3F10.5 )
WRITE( LOG, 25 ) FORCE, MINBHF, MAXBHF
25 FORMAT( 'FORCE, MINBHF, MAXBHF: ', F10.3, 2F10.1 )
WRITE( LOG, 30 ) STARTTIME, N_TH, PAIR
30 FORMAT( 'STARTTIME, N_TH, PAIR: ', 3I10)
WRITE( LOG, 35 )
35 FORMAT('Timestep,time,error,sumerror,slope,deltabhf, bhphistory,force,punch,pambhf')

ENDIF

******************************************************************************
C Proportional, Integral, Derivative Controller
******************************************************************************

C Check to see if it is time to begin control.
C
Find the error (proportional), sum of previous errors (integral), and
slope (derivative)
C
PUNCH = CONFORCE(3,PAIR)

IF (STARTTIME .LT. 0) THEN
  IF (PUNCH .GE. FORCE) BEGIN=.TRUE.
ELSE
  IF (Timestep .GT. STARTTIME) BEGIN=.TRUE.
ENDIF

IF (BEGIN) THEN
  AVGPUNCH = AVGPUNCH + PUNCH
  NTMS = NTMS + 1

C Average N_TH steps before attempting control action
C
IF ( NTMS .GE. N_TH ) THEN
  PUNCH = AVGPUNCH / NTMS
  NTMS = 0

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AVGPUNCH = 0.0
C
ERROR = FORCE - PUNCH
SUMERROR = SUMERROR + ERROR
SLOPE = PUNCH - PUNCHPREV
PUNCHPREV = PUNCH
C
Now calculate the binder load adjustment DELTABHF. This is
calculated by summing the proportional, integral, and derivative
values by their proportionality constants and then dividing by
STRESSLIMIT to obtain a unitless value.
C
DELTABHF = KP*ERROR + KI*SUMERROR + KD*SLOPE
BHFHISTORY = BHFHISTORY + DELTABHF
C
Adjust the binder load curve #2 by DELTABHF.
C
NCURSL = 2
DO 400 ICUR = 1, NUMCUR
   NCUR = LABCUR(ICUR)
   IF (NCUR.EQ. NCURSL) THEN
      BHFINITIAL=FUNVAL(ICUR)
      FUNVAL(ICUR) = BHFHISTORY + FUNVAL(ICUR)
      IF (FUNVAL(ICUR) .LT. MINBHF) THEN
         FUNVAL(ICUR) = MINBHF
         BHFHISTORY = MINBHF - BHFINITIAL
      ENDIF
      IF (FUNVAL(ICUR) .GT. MAXBHF) THEN
         FUNVAL(ICUR) = MAXBHF
         BHFHISTORY = MAXBHF - BHFINITIAL
      ENDIF
      PAMBHF = FUNVAL(ICUR)
   ENDIF
400   CONTINUE
C
Output values to the log file
C
WRITE ( LOG, 450 ) TIMESTEP, TIME, ERROR, SUMERROR, SLOPE,
       DELTABHF, BHFHISTORY, FORCE, PUNCH, PAMBHF
450   FORMAT( I10, 9(1h,F10.5) )
C
ENDIF
C
Adjust the binder load curve #2 by DELTABHF again.
C
NCURSL = 2
DO 500 ICUR=1,NUMCUR
   NCUR = LABCUR(ICUR)
   IF (NCUR.EQ. NCURSL) THEN
      FUNVAL(ICUR) = BHFHISTORY+FUNVAL(ICUR)
   ENDIF
500   CONTINUE
C
ENDIF
TIMESTEP = TIMESTEP + 1
C
RETURN
END

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APPENDIX H

DELIVERABLES FOR THE NEAR ZERO STAMPING PROJECT

Table H.1 lists the deliverables of the NZS project which include reports, cases studies, databases, modules and software. Tables H.2 through H.4 are lists of reports that have been written over the last four years of the Near Zero Stamping project. Table H.5 lists the content of the experience/sensitivity database which include the final results of laboratory and industrial simulations and experiments. Finally, Tables H.6 through H.8 contain the project plans for each of the three tasks of NZS charged to the ERC/NSM.

<table>
<thead>
<tr>
<th>REPORTS</th>
<th>MULTI-MEDIA MODULES</th>
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<tbody>
<tr>
<td>Task 1.2 Simulation Reports (8)</td>
<td>Bend Module</td>
</tr>
<tr>
<td>Task 1.3 Sensitivity Reports (8)</td>
<td>Deep Draw Module</td>
</tr>
<tr>
<td>Task 1.4 Hemming Reports (7)</td>
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<tr>
<th>PROGRAMS</th>
<th>FUNDAMENTAL MODULES</th>
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<tbody>
<tr>
<td>Bend, Flange Program</td>
<td>Sheet Forming as a System</td>
</tr>
<tr>
<td>Drawbead Force/Geometry Calculator</td>
<td>Bending, Flanging, Hemming</td>
</tr>
<tr>
<td>BHF Profile Calculator</td>
<td>Part &amp; Process Design for Stamping</td>
</tr>
<tr>
<td>Sheet Forming Design System</td>
<td>Product Quality</td>
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<tr>
<td>SectionForm 2D FEM</td>
<td>Recent Technologies</td>
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<td>Adaptive Simulation</td>
<td>Industrial Case Studies</td>
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<tr>
<th>DATABASES</th>
<th>MANAGEMENT ISSUES</th>
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<tr>
<td>Experience/Sensitivity Database</td>
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<tr>
<td>Hemming Database</td>
<td></td>
</tr>
<tr>
<td>Glossary of Terminology</td>
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<td>Publications Database</td>
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<th>INDUSTRIAL BETA TESTS</th>
<th>INDUSTRIAL CASE STUDIES</th>
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<tr>
<td>Cab Corner DOE Investigation</td>
<td>LHS and Caravan Door Outer</td>
</tr>
<tr>
<td>GM Wheel House Beta Test</td>
<td>Honda Wheel House</td>
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<tr>
<td></td>
<td>Deck Lid Outer</td>
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<td></td>
<td>Roof Panel</td>
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<tr>
<td></td>
<td>Fender Outer</td>
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<td></td>
<td>Cabin Inner</td>
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<td></td>
<td>Instrument Panel</td>
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Table H.1: List of Near Zero Stamping deliverables
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<tr>
<th>#</th>
<th>STATUS</th>
<th>TITLE / AUTHOR</th>
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<tbody>
<tr>
<td>1</td>
<td>S-97-R-005</td>
<td>A Systematic Approach to Automotive Stamping Design With Finite Element Analysis by Mark Diller</td>
</tr>
<tr>
<td>2</td>
<td>S-97-R-012</td>
<td>Evaluating Failure Criteria Using Computer Simulation by Sylvain Lemercier</td>
</tr>
<tr>
<td>3</td>
<td>S-98-R-012</td>
<td>Validation and Application of FE Simulation for Stamping Process Design by Toshi Oenoki</td>
</tr>
<tr>
<td>4</td>
<td>S-98-018A</td>
<td>Design, Validation, Machine Tool Path Planning, Construction, Simulation And Tryout of an Asymmetric Stretch Draw Die Set by Carmen Crowley</td>
</tr>
<tr>
<td>5</td>
<td>S-98-R-23</td>
<td>Guidelines and Recommendation on the Use of the FEM Code Pam-Stamp With Explanation of Features by Thomas Schmidt</td>
</tr>
<tr>
<td>6</td>
<td>S-98-R-24</td>
<td>Simulation of the Effect of Blank Shape Geometry and Mesh Configuration on Deep Drawing Using the FEM Code Pam-Stamp by Thomas Schmidt</td>
</tr>
<tr>
<td>7</td>
<td>S-99-R-15</td>
<td>Product and Process Design Methodology for Deep Drawing and Stamping of Sheet Metal Parts by William Thomas</td>
</tr>
<tr>
<td>8</td>
<td>S-99-R-??</td>
<td>Industrial Case Studies on Deep Drawing and Stamping of Complex Shapes Using Steel and Aluminum by Tolga Uludag</td>
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</table>

Table H.2: List of reports for NZS Task 1.2 - Simulation

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<th>#</th>
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<tr>
<td>1</td>
<td>S-96-33</td>
<td>State of the Art Review: Stamping Parameters and Their Effect on Sheet Metal Formability by William Thomas</td>
</tr>
<tr>
<td>2</td>
<td>S-97-R-007</td>
<td>Sensitivity Analysis of an AKDQ Steel Rectangular Deep Drawn Panel by Carlos Alvarado</td>
</tr>
<tr>
<td>3</td>
<td>S-97-08</td>
<td>Improving the Deep Drawability of 2008-T4 Aluminum and 1008 AKDQ EG Steel with Location Variable Blank Holder Force Control by William Thomas</td>
</tr>
<tr>
<td>4</td>
<td>S-98-R-10</td>
<td>Improving the Drawability of a Dome Cup Using Blank Holder Force Control by Peter Riegler</td>
</tr>
<tr>
<td>5</td>
<td>S-98-R-018</td>
<td>Investigation of Process Variables in Deep Drawing of Round Cups and Asymmetric Stamping Design and Tryout by Carmen Crowley</td>
</tr>
<tr>
<td>7</td>
<td>S-99-R-36</td>
<td>Sheet Metal Forming and Stamping Glossary by Serhat Kaya</td>
</tr>
<tr>
<td>8</td>
<td>S-99-R-35</td>
<td>Selected Technical Papers on Sheet Metal Forming by Serhat Kaya</td>
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Table H.3: List of reports for NZS Task 1.3 - Sensitivity
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<th>#</th>
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<tbody>
<tr>
<td>1</td>
<td>S-97-R-015</td>
<td>Bending, Flanging and Hemming of Steel and Aluminum Sheets - Progress Report I by Attila Muderissoglu.</td>
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<tr>
<td>2</td>
<td>S-97-R-017</td>
<td>Flanging and Hemming of Steel and Aluminum Sheets - Progress Report II by Haydar Livatyali.</td>
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<tr>
<td>3</td>
<td>S-97-R-022</td>
<td>Flanging and Hemming of Steel Sheets - Progress Report III by Thomas Laxhuber.</td>
</tr>
<tr>
<td>4</td>
<td>S-99-R-16</td>
<td>Flanging And Hemming Of Flat Surface-Straight Edge And Convex Edge Steel Sheets Progress Report IV by Haydar Livatyali and Seth Larris.</td>
</tr>
<tr>
<td>6</td>
<td>S-99-R-30</td>
<td>Investigation of Key Characteristics of Flanging and Hemming of Flat Surface - Curved Edge Sheet Metal by Seth Larris.</td>
</tr>
<tr>
<td>7</td>
<td>S-99-R-37</td>
<td>Analytical and Numerical Investigations of Sheet Metal Bending, Flanging and Hemming by Hsien-Chih Wu.</td>
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Table H.4: List for reports for NZS Task 1.4 - Hemming

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<tr>
<th>PART GEOMETRIES</th>
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<td>Bending</td>
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<tr>
<td>Flanging</td>
<td>Computer Simulations</td>
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<td>Hemming</td>
<td>Laboratory Experiment</td>
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<td>Drawbeads</td>
<td>Analytical Equations</td>
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<td>U-Channel</td>
<td>Forming Limit Diagrams</td>
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<td>Hemispherical Domes</td>
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<tr>
<td>Round Cups</td>
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<tr>
<td>Rectangular Pans</td>
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<td>Asymmetric Panel</td>
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<td>Cab Corner</td>
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Table H.5: Contents of experience/sensitivity database
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<td>1</td>
<td>Asymmetric tooling</td>
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<tr>
<td>1.1</td>
<td>Design and validate tooling</td>
<td>Crowley</td>
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<td>1.2</td>
<td>Develop CNC cutter paths</td>
<td>Fernandez</td>
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<td>1.3</td>
<td>Machine &amp; construct tooling</td>
<td>Burbick</td>
<td>100%</td>
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<td>1.4</td>
<td>Tool tryout</td>
<td>Burbick</td>
<td>100%</td>
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<tr>
<td>1.5</td>
<td>Simulate rabbit earing</td>
<td>Shunping/Crowley</td>
<td>100%</td>
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<tr>
<td>2</td>
<td>Process evaluation</td>
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<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Door panels 1 and 2</td>
<td>Diller</td>
<td>100%</td>
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<tr>
<td>2.2</td>
<td>Deck lid</td>
<td>Xinjun</td>
<td>100%</td>
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<tr>
<td>2.3</td>
<td>Cabin inner simulations</td>
<td>Oenoki</td>
<td>100%</td>
</tr>
<tr>
<td>2.4</td>
<td>Fender hard die tryout simulations</td>
<td>Oenoki</td>
<td>100%</td>
</tr>
<tr>
<td>2.5</td>
<td>Roof panel elastic instability simulations</td>
<td>Crowley</td>
<td>100%</td>
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<td>Product evaluation</td>
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<td>Wheel housing</td>
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<tr>
<td>3.2</td>
<td>Fast_FORM3D (one-step FEM) validation</td>
<td>Oenoki</td>
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<td>3.3</td>
<td>Blank shape prediction</td>
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<td>3.4</td>
<td>Dent resistance investigation</td>
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<td>Tufecki Thomas</td>
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<td>Failure analysis</td>
<td>Lemercier</td>
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<td>4.3</td>
<td>Gravity and binder wrap simulation</td>
<td>Oenoki</td>
<td>100%</td>
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<tr>
<td>4.4</td>
<td>Springback evaluation</td>
<td>Oenoki/Shunping</td>
<td>100%</td>
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<tr>
<td>4.5</td>
<td>Geometry translation &amp; hypermeshing</td>
<td>Oenoki/Shunping</td>
<td>100%</td>
</tr>
<tr>
<td>4.6</td>
<td>Simulation of press and die deflection</td>
<td>Thomas</td>
<td>100%</td>
</tr>
<tr>
<td>4.7</td>
<td>Prediction of optimal BHF profiles</td>
<td>Thomas</td>
<td>100%</td>
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<tr>
<td>5</td>
<td>Deliverable</td>
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<tr>
<td>5.1</td>
<td>Handbook based training</td>
<td>Thomas</td>
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<td>Web based training</td>
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<tr>
<td>5.3</td>
<td>Beta test of wheel housing</td>
<td>Jiratheeranat</td>
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Table H.6: Project plan for NZS Task 1.2 - Simulation
<table>
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<th>SUBTASK</th>
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<tr>
<td>1</td>
<td><strong>Round tooling</strong></td>
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<tr>
<td>1.1</td>
<td>Sensitivity simulations with Pam-Stamp</td>
<td>Shunping</td>
<td>100%</td>
</tr>
<tr>
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<td>Sensitivity experiments</td>
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<td>100%</td>
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<td>Tailor welded blanks</td>
<td>Shulkin</td>
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<td><strong>Dome tooling</strong></td>
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<td>Drawability experiments and simulations</td>
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<td>Location variable BHF, shallow flat panel</td>
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Table H.7: Project plan for NZS Task 1.3 - Sensitivity
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Table H.8: Project plan for NZS Task 1.4 - Hemming