Improvement of Stamping Operations by using Servo Press and Servo Hydraulic Cushion

– Case Studies

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in
the Graduate School of The Ohio State University

By

Pratik Mehta

Graduate Program in Industrial and Systems Engineering

The Ohio State University

2017

Dissertation Committee:

Dr. Taylan Altan, Advisor

Dr. Jerald Brevick
Abstract

Sheet Metal forming is facing many difficult problems such as forming of hard formable materials with high strength and low ductility, high precision forming and improvement of productivity. Due to the recent development, there has been increase in the use of servo presses and servo cushions. The use of servo press is expected to improve tool-life, increase productivity, improve processing accuracy, reduce noise and vibration, develop complex processes and shorten forming processes. New forming techniques have been developed utilizing the characteristics of servo press and servo cushions. This thesis studies whether the drawability of the part can be improved by using (a) Servo Press and Servo Cushion characteristics such as Attach – Detach, variable blank holder force and Pulsating blank holder force and (b) optimum slide velocity and forming conditions (lubrication, blank holder force and blank size).

Two forming examples have been studied. FE simulations using PAMSTAMP 3D and experimental tryouts using Servo Press and Servo Cushions have been carried out and formed samples have been evaluated to determine whether drawability can be improved by using servo press and servo cushion characteristics.
The overall conclusions on the study are:

**Attach –Detach:** Ram Motion can influence the drawability of the material. Results show that for some material and tool geometry, Attach – Detach may improve drawability. However, additional studies are needed to understand this observation.

**Cushion Pulsation:** Cushion Pulsation improve the drawability by improving the lubrication condition and by reducing friction in the flange. However, the applicability of cushion pulsation maybe be limited to small tool geometries and the long range dependability should be considered.

**Ram Speed:** For certain tool geometry and material, using fast ram speed improve the drawability by improving the lubrication conditions (Certain additives in the lubricant can perform better at high temperatures).

**Ram Speed type:** Ram motion type can significantly affect the cushion response specifically when the die starts to touch the material. To provide the best cushion response the die should touch the material as slow as possible and then the speed should be increased to maintain the required cycle time.

**Improvement in blank shape:** Using PAMSTAMP inverse analysis, uniform flange shape is obtained. We should use PAMSTAMP to optimize the blank shape in future
Acknowledgments

I would like to thank the department of Industrial and Systems Engineering, The Ohio State University for giving me the necessary resources to hone my skills as an engineer and complete my studies at The Ohio State University. I would like thank Dr. Taylan Altan for his guidance, patience and kindness in helping me to mold myself into a better engineer and for giving me the opportunity to work at the Center for precision forming. I sincerely thank Dr. Jerald Brevick, for all his inputs and support during my study.

I would like to thank my colleagues Ali Fallahiarezoodar and David Alberto Diaz Infante Hernandez for helping, advising and guiding me continuously during my course of study. I would also like to extend special thanks to Aanandita katre, Berk Aykas, Zeming Yin and Suraj Appachu for their guidance. I would also like to thank other students and members of CPF with whom I had a pleasure working with.

I thank my family and friends for all their support during my course work.
Vita

2013.................................................................B.E Mechanical Engineering

.................................................................PVG’s COET, Pune

2015 to present ..............................................Graduate Research Associate, Department
   of Industrial and Systems Engineering, The
   Ohio State University

Publications

Ali Fallahiarezoodar, Darrell Quander Jr., Pratik Mehta and Dr. Taylan Altan “Practical
use of Servo Hydraulic Cushions in Stamping Operations”, Stamping Journal – March /
April 2007, Page 16-17

Fields of Study

Major Field: Industrial and Systems Engineering
Table of Contents

Abstract .................................................................................................................................................. ii

Acknowledgments ................................................................................................................................. iv

Vita ......................................................................................................................................................... v

Table of Contents .................................................................................................................................. vi

List of Tables .......................................................................................................................................... xi

List of Figures ......................................................................................................................................... xiii

Chapter 1: Introduction ............................................................................................................................ 1

1.1 Using Spacers (stand-offs or position stops) to improve drawability ........................................... 3

1.2 Using CNC hydraulic Cushions ...................................................................................................... 4

Chapter 2: Research Objectives and Approach ..................................................................................... 6

Chapter 3: Literature review .................................................................................................................... 8

3.1 Servo Press and Servo Cushions .................................................................................................... 8

3.1.1 Forming Speed ............................................................................................................................ 12

3.1.2 Relaxation of the material ......................................................................................................... 14

3.1.3 Attach – Detach (A-D) mode .................................................................................................... 17
3.1.4 Cushion Pulsation ................................................................. 22

3.1.5 Bottoming and Re-striking in Bending ....................................... 25

3.2 Material Properties / Lubrication ..................................................... 27

3.2.1 Determination of material properties by the uniaxial tensile test ........ 27

3.2.2 Determination of material properties by the viscous pressure bulge (VPB) test
.................................................................................................................. 30

3.2.3 Tests for evaluation of lubricants .................................................. 31

Chapter 4: Deep Drawing with Hyson Die – Stainless Steel Material ............ 36

4.1 Objectives and Approach .................................................................. 36

4.1.1 Objective ..................................................................................... 36

4.1.2 Approach .................................................................................... 37

4.2 Finite Element Simulations ............................................................... 38

4.2.1 Criterion for prediction of wrinkles .............................................. 38

4.2.2 Determination of optimum blank holder force ................................ 39

4.2.3 Simulation of Hyson part geometry .............................................. 41

4.2.4 Comparison of simulation results (variable and constant BHF and simulation
with spacer) ......................................................................................... 45

4.2.5 Comparison of variable BHF predicted by CPF and Hyson BHF (without
spacers) ............................................................................................... 51
4.2.6 Comparison of simulation results with Hyson part without spacers (validation) .................................................................................................................. 55

4.3 Experimental Investigation (no spacers were used) ........................................ 59

4.3.1 Forming with variable and constant blank holder force .................................. 60

4.3.2 Forming with Attach-Detach Method and Speed effect .................................. 63

4.3.3 Results of experiments ..................................................................................... 66

4.4 Comparison of experimental results with simulations (no spacers) .................. 67

4.4.1 Measurement of Draw-in ................................................................................ 67

4.4.2 Measurement of thickness distribution .............................................................. 71

4.5 Comparison of target BHF (input to press) versus actual BHF (output/measured from the press) .............................................................................. 74

4.6 Summary and Conclusions .................................................................................. 77

4.6.1 Summary ........................................................................................................... 77

4.6.2 Conclusions ...................................................................................................... 78

Chapter 5: Deep Drawing with Hyson Die – Steel Material .................................... 79

5.1 Objectives and Approach .................................................................................... 79

5.1.1 Objectives ........................................................................................................ 79

5.1.2 Approach ......................................................................................................... 79

5.2 Finite Element Simulations using PAMSTAMP 3D ........................................ 80
5.2.1 Input parameters in the simulation ................................................................. 80

5.2.2 Simulation with constant blank holder force and comparison with forming limit diagram .................................................................................................................. 82

5.3 Experimental Investigation (no spacers were used) ............................................. 84

5.3.1 Forming with constant blank holder force to obtain optimum blank geometry 84

5.3.2 Forming with pulsating blank holder force ..................................................... 87

5.4 Comparison of target blank holder force (input to press) versus actual blank holder force (output / measured from the press) ......................................................... 88

5.4.1 Cushion Response – Constant blank holder force ........................................ 89

5.4.2 Cushion Response – Pulsating BHF ............................................................... 90

5.5 Summary and Conclusions ............................................................................... 92

5.5.1 Summary ....................................................................................................... 92

5.5.2 Conclusions .................................................................................................. 92

Chapter 6: Deep Drawing with Honda Die – Aluminum Material ............................ 94

6.1 Objectives and Approach ............................................................................... 94

6.1.1 Objectives .................................................................................................... 94

6.1.2 Approach ..................................................................................................... 95

6.2 FE simulation model of Honda geometry using PAMSTAMP 3D ............. 96

6.2.1 Evaluation of accuracy of forming limit diagram (FLD) ....................... 97
6.2.2 Determination of optimum constant blank holder force with and without
spacers and effect of spacer height on thinning........................................... 100

6.2.3 Determination of parameters of using variable BHF............................ 105

6.2.4 Results of simulations........................................................................... 106

6.3 Experimental set up and samples preparation.......................................... 106

6.3.1 preparation of initial blanks and tool set up ......................................... 108

6.3.2 Forming with and without spacers (geometry B)................................. 112

6.3.3 Forming without spacers (blank geometry A & C)............................... 115

6.3.4 Results of experiments........................................................................... 117

6.4 Comparison of simulation results with experimental tryouts............... 118

6.4.1 Based on maximum thinning................................................................. 118

6.5 Comparison of target BHF (input to press) versus actual BHF (output / measured
from press).................................................................................................. 120

6.5.1 Ram motion used.................................................................................. 120

6.5.2 Servo Cushion response – Constant BHF............................................. 121

6.6 Summary and Conclusions...................................................................... 123

6.6.1 Summary............................................................................................... 123

6.6.2 Conclusions.......................................................................................... 123

References...................................................................................................... 125

x
List of Tables

Table 1: Input parameters in the simulation ................................................................. 41
Table 2: Different cases and value of maximum thinning obtained from simulations ... 46
Table 3: Comparison of wrinkle heights obtained from simulations ......................... 47
Table 4: Comparison of wrinkle heights obtained from simulation ......................... 53
Table 5: Summary of results obtained from variable and constant blank holder force experiments .......................................................................................................................... 61
Table 6: Tabular summary of results obtained from attach-detach experiments .......... 64
Table 7: Details of different cases .............................................................................. 68
Table 8: Input data to simulation .............................................................................. 81
Table 9: Results obtained with different blank geometries ..................................... 86
Table 10: Experimental results with Pulsating blank holder force ......................... 88
Table 11: Input parameters for Barlat 2000 yield criteria, obtained from (Carsley et al., 2013) .................................................................................................................. 97
Table 12: Input parameters in simulation .................................................................. 99
Table 13: Results of simulation with and without spacer ....................................... 102
Table 14: Clearance values measured at different locations measured between punch and die ......................................................................................................................... 111
Table 15: Experimental results when forming without spacers using blank geometry A & C
List of Figures

Figure 1: The effect of BHF/stroke curve in determining drawability without tearing (fracture) wrinkling [4] ........................................................................................................................................ 1

Figure 2: Two methods for applying BHF in deep drawing of sheet material. Left: use of spacer, right: use of CNC cushions system [26] ........................................................................................................ 2

Figure 3: Schematic of the intelligent tools used at Audi to control the drawing by modifying the spacer height during the drawing process [26] ................................................................................. 4

Figure 4: Typical Slide motions of servo-press [23] ........................................................................................................... 9

Figure 5: Decrease in cycle time as well as in impact speed using a servo press (150% increase in output) [23] ................................................................................................................................. 9

Figure 6: Path-time curves using a servo-screw press and CNC servo-cushion [13] ...... 10

Figure 7: Slide motion graph for different modes: conventional (V-mode), stress relaxation (U and stepwise modes), and Attach-Detach mode (improving lubrication) [16] ........................................................................................................................................... 11

Figure 8: Improvement of forming 6 xxx series aluminum door inner panel using servo press; left – panel formed at low velocity (41mm/sec); right – panel formed at high velocity (203mm/sec)[6] .............................................................................................................................................. 12
Figure 9: Variation of the COF with the speed at different contact pressures (in a strip draw test) [20].......................................................... 13
Figure 10: Increment of the temperature when the forming speed increases [20]............. 14
Figure 11: Total elongation improvements due to stress relaxation [5].............................. 15
Figure 12: Stress relaxation effect, along the strain axis [5]............................................. 16
Figure 13: COF vs Contact Pressure [17]...................................................................... 18
Figure 14: Springback profiles at different detachment strokes [14]............................... 19
Figure 15: Improvement of deep drawability of high strength steel sheet by detachment of tools from sheet during forming [29]....................................................... 20
Figure 16: Prevention of wrinkling in deep drawing by stepwise motion [12]................. 20
Figure 17: Large reduction in thickness in ironing of aluminum cup by stepwise motion [11]................................................................................................................. 21
Figure 18: Prevention of fracture in cold stamping by control of ram motion [22]........... 22
Figure 19: Comparison of deep drawn cylindrical cups (1mm DCO4) for different drawing ratios [13]................................................................. 23
Figure 20: Comparison between conventional deep drawing and cushion ram-pulsation [13]............................................................................................................. 24
Figure 21: Ram Motions for reducing springback in bending of sheet metal [21]......... 25
Figure 22: Reduction in springback by bottoming in V-shaped bending of 980MPa level ultra – high strength steel sheet [21]......................................................... 26
Figure 23: Reduction in springback and twisting by re-striking in bending of channel shaped product [27]................................................................. 27
Figure 24 : Tensile test specimen according to ASTM E8/E8M-09 [18] .............................. 27
Figure 25 : Set up for tensile test [33]............................................................................. 28
Figure 26 : geometry before and after the test (t0 = original sheet thickness, td = sheet thickness at the apex , hd = bulge height , P = hydraulic pressure, rc = die fillet radius , dc = die cavity diameter , rd = radius of curvature) [30].......................................................... 30
Figure 27 : Schematic of the left shows the sheet clamped between the upper and lower die. Schematic on the right shows the sheet bulged by the pressurizing medium into the upper die cavity [30]........................................................................................................... 31
Figure 28 : Schematic of cup drawing [10] ........................................................................... 32
Figure 29 : Schematic of CDT tooling at CPF [28]................................................................. 33
Figure 30 : Schematic of limit dome height test [32] ............................................................. 35
Figure 31: Change in the location of maximum thinning with increased COF [32] ........... 35
Figure 32: Hyson Die Geometry ......................................................................................... 36
Figure 33: Dimensions of Hyson Part ................................................................................ 37
Figure 34: Method of measuring wrinkles in simulation...................................................... 38
Figure 35: Location of planes taken for measurement of wrinkles in simulation .............. 39
Figure 36: Flow chart of methodology to determine optimum blank holder force .......... 40
Figure 37: Flow stress curve obtained from bulge test conducted at CPF......................... 42
Figure 38: Flow curve of load applied on blank from blank holder in simulation with spacer .................................................................................................................................................................................. 43
Figure 39: Flow curve of variable blank holder force obtained using the methodology in Figure 36 ............................................................................................................................................................................ 44
Figure 40: Maximum thinning location obtained from simulations .............................................. 45
Figure 41: Wrinkle comparison on part for different cases ....................................................... 47
Figure 42: Stroke versus thinning comparison for different cases ........................................... 48
Figure 43: Comparison of thinning distribution obtained from variable and constant BHF (no spacers) .......................................................................................................................... 49
Figure 44: Comparison of thinning distribution obtained from variable BHF and using spacers ........................................................................................................................................ 49
Figure 45: Comparison of Hyson variable blank holder force versus CPF variable blank holder force .................................................................................................................................. 51
Figure 46: Stroke versus thinning comparison ............................................................................ 52
Figure 47: Location of section in simulation where maximum thinning is obtained ............... 55
Figure 48: Photo of cut sample and measurement line shown .................................................. 56
Figure 49: Comparison of experiment thinning results with simulation thinning results. 57
Figure 50: Location of the data points on the Hyson part .......................................................... 57
Figure 51: Photo of Komatsu Servo Press and tooling at Hyson .............................................. 59
Figure 52: CPF and Hyson variable blank holder force curves used in experiments ............. 60
Figure 53: Summary of results obtained from variable and constant blank holder force experiments .................................................................................................................................. 62
Figure 54: Attach-detach method used ...................................................................................... 63
Figure 55: Schematic showing attach-detach principle .............................................................. 63
Figure 56: Schematic of results obtained from attach-detach .................................................. 65
Figure 57: Schematic of change in fracture location with different press speeds ............... 65
Figure 58: Method used to measure draw-in in x and y direction ................................. 67
Figure 59: Graph of results obtained from draw-in measurements in x direction .......... 68
Figure 60: Graph of results obtained from draw-in measurements in y direction ........ 69
Figure 61: Comparison of experimental and simulation results obtained from draw-in measurements in x direction .................................................................................................. 70
Figure 62: Comparison of experimental and simulation results obtained from draw-in measurements in y direction .................................................................................................. 70
Figure 63: Location of points taken on part for thickness measurement ...................... 71
Figure 64: Location of the data points on the Hyson part ............................................. 72
Figure 65: Measurement of thickness distribution in experiment ............................... 72
Figure 66: Thickness distribution comparison of experimental and simulation results .. 73
Figure 67: Comparison of Target cushion BHF (input to the press) versus actual cushion BHF (output/measured from the press) .................................................................................................. 74
Figure 68: Comparison of Target blank holder force versus actual blank holder force for 100KN BHF and ram speed of 11SPM .................................................................................................. 75
Figure 69: Comparison of Target blank holder force versus actual blank holder force for 100KN BHF and ram speed of 19SPM .................................................................................................. 76
Figure 70: Flow Stress curve used in simulations for Steel A1008 CRS Type B, 1mm [Tensile test has been conducted at CPF] .................................................................................................. 81
Figure 71: Formulae used for calculation of initial blank holder force [1] ...................... 82
Figure 72: Maximum thinning and thinning location in simulations with Steel A1008 CRS Type B material .......................................................................................................................... 83
Figure 73: Comparison of simulation results with forming limit diagram ........................................... 83
Figure 74: Different blank geometries tested in experiments .......................................................... 85
Figure 75: Difference between preliminary and optimized blank geometry and results obtained with blank geometries ................................................................................................................. 87
Figure 76: Ram motion used in experiments ...................................................................................... 89
Figure 77: Cushion response when using constant 50kN blank holder force ..................................... 90
Figure 78: Cushion response when using Pulsating blank holder force (Amplitude 85kN to 20kN and frequency 5 hertz/sec) .................................................................................................................. 91
Figure 79: Cushion response when using Pulsating blank holder force (Amplitude 85kN to 20kN and frequency 15 hertz/sec) ................................................................................................................. 91
Figure 80: Schematic of Honda Die Tooling ....................................................................................... 95
Figure 81: Flow Stress Data (combined tensile and bulge test data) used in simulations.................. 97
Figure 82: Forming limit curve of Al 5182-O, with thickness of 1.1mm, obtained from [Carsley et al, 2013] ...................................................................................................................................................... 98
Figure 83: Simulation result compared with FLD at 80mm draw depth ........................................... 100
Figure 84: Blank geometries used in simulations ............................................................................. 101
Figure 85: Simulation results using no spacers and 350kN constant blank holder force with different geometries ................................................................................................................................. 103
Figure 86: Maximum thinning location in simulations (Blank shape B) ............................................ 104
Figure 87: Flange shape at 120mm draw depth for different blank geometries ............................... 104
Figure 88: Load applied on the blank holder by the blank when using spacers .............................. 105
Figure 89: Photo of 300 Ton Komatsu servo press with 100 Ton CNC hydraulic cushion at Hyson .......................................................... 107

Figure 90: Honda die mounted inside the Hyson Press ............................................. 108

Figure 91: Lead wires located on punch to measure the clearance between punch and die ........................................................................................................... 110

Figure 92: Positions where clearance between punch and die were measured............ 110

Figure 93: Experimental results when forming with and without spacers using constant and variable blank holder force ........................................................................................................... 112

Figure 94: (A) Wrinkles entering the die when forming with spacers (B) less wrinkles observed when forming without spacers and using constant and variable blank holder force ........................................................................................................... 113

Figure 95: Variable blank holder force used in experiments ...................................... 114

Figure 96: Schematic of spacers locations used in experiments .................................. 114

Figure 97: Photo of spacers and location of spacers used in experiments ............... 115

Figure 98: Improvement in blank shape/size obtained when using PAMSTAMP inverse analysis ........................................................................................................... 117

Figure 99: Comparison of simulation and experimental results based on maximum thinning ........................................................................................................... 119

Figure 100: Location of samples cut for measurement of maximum thinning in experiments ........................................................................................................... 120

Figure 101: (A) Ram slowed down motion when die touches the blank (B) Ram motion during the entire stroke ........................................................................................................... 121
Figure 102: Servo cushion response when using constant 350 KN blank holder force 122
Chapter 1: Introduction

In deep drawing, with or without draw beads, the sheet metal blank is subjected to restraining force at its periphery by the blank holder while it is forced to flow into the die cavity by the punch. The quality of a formed part is determined by the amount of material drawn into the die cavity. Excessive material flow and low blank holder force (BHF) may cause wrinkling and insufficient material flow will cause excessive thinning which may cause tearing or fracture, as shown in Figure 1, for the example of using a constant BHF.

Figure 1: The effect of BHF/stroke curve in determining drawability without tearing (fracture) wrinkling [4]
In general, the BHF is generated by one or more pneumatic or hydraulic cylinders and is transmitted via the pressure box and cushion pins to the blankholder. In using new generations of materials with higher strength and lower ductility, i.e. advanced high strength steels and 6xxx and 7xxx aluminum alloys, forming a complex geometry requires precise control of material flow into the die cavity. There are two different methods to control metal flow in drawing:

a) use of spacers (stand-off blocks) with specific height, and b) use of variable blank holder force by using a CNC cushion system, Figure 2.

![Figure 2: Two methods for applying BHF in deep drawing of sheet material. Left: use of spacer, right: use of CNC cushions system [26]](image)

**Pneumatic (Air) cushion and nitrogen cylinder**

In using a pneumatic cushion (air cushion), the BHF is generated by moving a piston activated by compressed air. Pneumatic cylinders are seldom used in modern presses because the maximum pressure in such a system is limited, usually to about 16 bar (240 psi) and a very large piston area is needed to generate the required force. Furthermore, it
is relatively difficulty to control the motion and pressure of a pneumatic cushion because the air is compressible. In pneumatic cushion systems, the BHF is constant and is applied instantaneously when the die contacts the blankholder or the blank. Therefore, usually spacers, that are 10 to 15% thicker than the initial blank thickness, are used, Figure 2. The nitrogen cylinders are built into the die and provide pressure and force that remains approximately constant during the forming operation.

1.1 Using Spacers (stand-offs or position stops) to improve drawability

When spacers are used, the die and blank holder are pressed against each other and the spacers while, at the start of the stroke, the blank is free to flow into the die cavity with the relative movement of the punch against the die. As deformation and punch stroke proceed, the edges of the blank become thicker and some minor wrinkling may occur in the flange region. The blank thickness and wrinkle height increase but cannot exceed the “clearance” between the die and blank holder, provided by the spacers. At this stage in drawing, the blank holder (binder) controls the material flow. The force exerted by the deforming blank upon the die and blank holder increases while the contact between the die, blankholder and spacers is maintained. The heights and locations of the spacers are usually determined during “try-out” through several trial and error stampings. Recently an “intelligent tool” has been developed at Audi. A laser sensor measures the flange draw-in. A control algorithm activates an adjustable spacer (possibly by a small servo motor) to the optimal value, Figure 3. This system is used to produce a striking angular
design of the aluminum bonnet for A3 series. Since 2012, around 20 other tools with this technology have been used in the Volkswagen Group.

Figure 3: Schematic of the intelligent tools used at Audi to control the drawing by modifying the spacer height during the drawing process [26]

1.2 Using CNC hydraulic Cushions

In hydraulic cushion systems, the required BHF is generated by pressurizing the hydraulic fluid. The BHF can be controlled in time and stroke (CNC control) controlling the oil flow to the cushion cylinder. Modern stamping presses can be equipped with CNC hydraulic cushions. These systems have the capability to vary the blank holder force during the press stroke. Thus, within the limits of inertia of the hydraulic systems, CNC cushions offer great flexibility, during the punch stroke, to control the metal flow from the flange into the die cavity. Some advantages of the CNC cushions include:

Pre-acceleration: Before the die hits the blank, it is desirable to reduce the relative velocity between the blank holder and the die. Thus, the cushion begins to travel in the direction of moving die (or punch) before the die contacts the blank and deformation starts. This capability:
a) Reduces sudden shock on the press and tooling,

b) Prevents the lubricant, applied on the blank from being disturbed and squeezed out.

**Variation of the BHF:** During the stroke, BHF variation would help to control metal flow into the die cavity to reduce wrinkles and prevent excessive thinning and fracture in the drawn part.

**Increase of the BHF:** Near the end of deformation process, allows increasing tensile stresses in the walls of the drawn part, thereby reducing springback.

**Possible elimination of draw beads:** In certain applications the BHF, controlled by the CNC cushion, may provide sufficient force to restrain excessive metal flow into the die cavity, thus reducing the amount of flange material to be trimmed.

**Providing restraining force:** It is possible to increase the amount of strain and hardening in drawing exterior body panels, thereby increasing dent resistance.

Several methods are being developed to estimate the BHF variation with press stroke. One method is through experimentation during try-out. The other is to use computer simulation that requires the ability to predict, with reasonable accuracy, the potential formation of wrinkles and fracture as well as the effect of BHF upon springback.
Chapter 2: Research Objectives and Approach

The overall objective of this study is to improve the drawability by using the optimum slide velocity and forming conditions (lubrication, blank holder force and blank size) in a servo press with CNC hydraulic servo cushion. The specific objectives are:

- **Material Properties:** Determine the material properties (flow stress, yield stress, ultimate tensile stress and elongation) for selected material (also input parameters for FE simulations)

- **Lubrication Condition:** Identify the best lubricant and surface conditions (texture) for reducing friction

- **Servo Press and Servo Cushion Characteristics:** Determine the possible advantages of the effect of (a) Attach – Detach (b) Pulsating blank holder force and (c) Variable blank holder force

To achieve the objectives, the following approach is followed:

- In Chapter 3, literature review on improvement of forming conditions by using servo press and servo cushions, determination of material properties and various tests for evaluation of lubricants has been carried out.

- In Chapter 4, deep drawing using Hyson Die using Stainless Steel 304 material has been studied. FE simulations and experimental tests have been conducted to
determine whether quality of formed part can be improved by using variable blank holder force and Attach – Detach.

- In Chapter 5, deep drawing using Hyson Die using Steel A1008 CRS Type B material has been studied. FE simulations and experimental tests have been conducted to determine the optimum blank shape/size and to determine whether drawability can be improved by using pulsating blank holder force.

- In Chapter 6, deep drawing using Honda Die and Aluminum 5182-O has been studied. FE simulations have been conducted with and without spacers and experiments have been conducted to determine the advantages/ disadvantages of using spacers (or no spacers) and the possible advantages of the effect of (a) Attach-Detach, (b) Pulsating blank holder force and (c) variable blank holder force.
Chapter 3: Literature review

3.1 Servo Press and Servo Cushions

Servo-press technology is relatively new to the industries compared to conventional press. Only few reports have addressed the effectiveness of the servo-press technology to improve the drawability. The ability to accurately control the slide movement is one of the most important feature of the servo press as shown in Figure 4. This capability can provide the following advantages [23]:

1) Since the motions such as crank press and linkage press can be duplicated by a servo press, the ram speed with the existing presses can be duplicated.

2) The tool life can be extended by reducing the touching speed of the tool to the work piece and reduce the impact loading

3) Lubrication is often improved and the drawability limit can be extended by using a pulsating or oscillating slide motion (if press dynamics allow this motion)

4) Touching and break-through noise is reduced by stopping the slide for a short time or reducing the slide speed

5) Higher productivity is possible by shortening of a forming cycle with a partial short stroke around bottom dead center as well as a high-speed return motion as shown in Figure 5.
Figure 4: Typical Slide motions of servo-press [23]

Figure 5: Decrease in cycle time as well as in impact speed using a servo press (150% increase in output) [23]
An overview of deep drawing techniques (mathematical sense) with variable stroke-time curves by using a servo-screw press and a CNC servo-cushion is reported. With this equipment, rapid changes of direction are feasible in the cushion, provided the dynamics (response time) of the press ram and cushion allow the rapid motions.

Figure 6 shows the different forming kinematics. [13]

![Figure 6: Path-time curves using a servo-screw press and CNC servo-cushion](image)

Some authors have investigated four of the main phenomena observed during sheet metal forming using the motion servo capability; relaxation of the material, relubrication
conditions due to attach-detach (A-D) mode, pulsating tooling (vibrations) and forming speed. These observations will be described below.

![Slide motion graph for different modes](image)

Figure 7: Slide motion graph for different modes: conventional (V-mode), stress relaxation (U and stepwise modes), and Attach-Detach mode (improving lubrication) [16]

It is possible to reduce significantly the blanking noise by using two steps blanking of stainless steel, titanium and copper. In these two steps blanking process, the punch is stopped in an intermediate position before breakthrough and then it starts its movement again to complete the blanking. [24]

It is possible to obtain a workpiece without burr by using three blanking steps in a servo press; half blanking, pushing back and blanking through. However, to obtain free-burr workpiece it is important to combine slide motion (re-striking) with the correct tooling geometry. [8]
3.1.1 Forming Speed

An improvement in forming an aluminum part (door inner) is observed when using servo press compared to the conventional press as shown in Figure 8. The formability of aluminum alloy is improved with the increase in forming velocity. Thus, high ram speed forming rate was used in the servo press. Also, they have shown that the acceleration of the slide velocity during the deformation stage improve the formability [6].

Figure 8: Improvement of forming 6 xxx series aluminum door inner panel using servo press; left – panel formed at low velocity (41mm/sec); right – panel formed at high velocity (203mm/sec)[6]

A study was conducted to analyze the effect of the speed, amount of lubricant (using strip draw test) and temperature on the COF during deep drawing operations in a servo press. The results indicate that sliding speed significantly affects the COF and the temperature on the part. Figure 9, shows how the COF decreases when the sliding speed increases; the same trend is observed for three different contact pressures. [20]
As observed in Figure 10, the temperature increases considerably at higher speeds. This phenomenon may be observed because when the speed increases, the part is less time in contact with the tooling; therefore, the heat transfer between the part and the tools is smaller. [20]
Figure 10: Increment of the temperature when the forming speed increases [20]

3.1.2 Relaxation of the material

Interrupting the forming cycle by adjusting the slide motion to create a stepped forming operation helps to improve the formability of the materials. The author claimed that by stepping the process the stresses on the material were released. This interpretation, however, is questionable. It is more probable that stepped motion of the punch reduces friction. [5]
Figure 11: Total elongation improvements due to stress relaxation [5]

The stress relaxation effect is also a function of the strain rate and the number of relaxation steps as shown in Figure 12. For the cases of low carbon steel and TRIP, strain rate equal to $10^{-2}$ leads to larger uniform elongations than the strain rate equal to $10^{-1}$; however, this phenomenon is not clearly appreciated for the case of the DP steel. It can be also observed that the uniform elongation increases when the number of steps increases. [5]
Figure 12: Stress relaxation effect, along the strain axis [5]

The stress relaxation improves the drawability of the material and it is important to optimize the slide stopping time in this kind of operations to keep a balance with the productivity. The capabilities of the servo press nowadays give the possibility to compensate this “stopping time” by accelerating the rest of the process. In this work, the deep drawing (rectangle cup) limit of steel types of 270-980MPa was significantly improved; from 50 mm to 60 mm in some cases. [31] The effect of stress relaxation with a conventional stamping mode (V-mode described in Figure 7 above) was compared. In this study DP780 was used; the results showed that the
stepwise motion (stress relaxation) is ineffective for reducing the springback in U-bending operations [16].

Later, the effect of the stress relaxation with the Attach-Detach (A-D) mode on springback in a draw bending operation for AHSS (DP780 and DP980) was compared. Again, it turned out that the effect of stress relaxation was almost insignificant. However, the results indicated that the springback can be reduced effectively by using the A-D mode (summarized in section 3.1.3) [14]

3.1.3 Attach – Detach (A-D) mode

The effect of the punch motion on drawability of AHSS sheets (TRIP780) was investigated by using cup draw test, the results indicated that the Attach-Detach (A-D mode) had a significant influence on the maximum drawing depth of the part due to a reduction of the coefficient of friction (COF) in a magnitude of 0.005 every time that the punch was detached from the metal sheet. The friction test determines that the COF decreases when the contact pressure increases as shown in Figure 13. In the A-D mode the cups were formed 12 percent larger than the cups of the conventional mode. [17]
Figure 13: COF vs Contact Pressure [17]

A new cup draw test was conducted which included two AHSS (TRIP780 and DP780), again the A-D mode turned out to be more effective than the traditional V-mode (described in Figure 7). The cups were formed 17 and 13 percent deeper using A-D mode for TRIP780 and DP780 respectively.

The effect of the A-D mode on the springback of a hat shape bending compared with the regular ram motion was investigated. The FE simulation and experimental results, indicated that the detachment of tools from the work piece is effective to reduce springback on the part. Furthermore, it was indicated that more important than the number of detachments is the position where the detachment occurs. Experiments and FE simulations showed a springback reduction when the detachment occurs almost at the end of the stroke (Figure 14) [14].
The formability of high strength steel sheets was improved by detaching the tools from the sheet during the deep drawing as shown in Figure 15. The sheet was automatically re-lubricated by the detachment. A 590MPa level high strength steel sheet is drawn by the detachment. [29]
Wrinkling in deep drawing can be prevented (Figure 16) by applying a stepwise motion. This leads to improvement of formability due to the reduction in blankholder force.

Figure 16: Prevention of wrinkling in deep drawing by stepwise motion [12]
The stepwise motion to reduce friction in ironing of cups was applied as shown in Figure 17. A large reduction in thickness in the ironing is attained by the stepwise motion. [11]

Figure 17: Large reduction in thickness in ironing of aluminum cup by stepwise motion [11]

The occurrence of fracture in cold stamping was prevented by controlling the ram motion as shown in Figure 18. First, the punch slowly touches the sheet, then a portion in contact with the corner of the punch is slightly shifted by reversing the ram motion, and thus local thinning is prevented. Although this product is conventionally formed by 2 stages, one stage is reduced by means of the servo press [22].
3.1.4 Cushion Pulsation

Friction between sheet and die can be minimized when superimposed vibrations are used. Vibration amplitudes are in few millimeters range at low frequency range up to 50 Hz. During pulsation, the maximum drawing force is reduced, therefore larger drawing ratios can be obtained. The possible tool motion is described in Figure 6. [7]

Amplitudes have to be decreased and frequency is adequately increased to achieve high productivity [13].
A comparison between conventional deep drawing and cushion-ram-pulsation of the cylindrical cup shows the increase of drawing ratios, Figure 19. For steel DC04 with an initial blank thickness of 1 mm drawing ratios of $\beta_{max} = 2.1$ and $\beta_{max} = 2.4$ could be reached, for conventional and cushion-ram-pulsation deep drawing, respectively [13].

The part shown in Figure 20 is made from 1mm thick steel DC04. The initial blank outline for standard deep drawing and cushion-ram-pulsation has the same size 680 mm by 430 mm. The conventional deep drawing ends up with a fracture at the bottom corner after 46 mm depth. A much larger drawing depth can be reached by applying cushion-ram pulsation with 30 Hz and amplitudes of 0.2 mm (ram) and 0.8 mm (cushion). [13]
Figure 20: Comparison between conventional deep drawing and cushion ram-pulsation [13]

According to [13], studies have shown that for high strength steel, an increase of up to a maximum of 20% in drawing depth can be achieved by means of a defined interruption of stroke.

The results demonstrate a stress relieve of the material as a function of time, independently of load speed and pre-stretch. In this arrangement, fracture in the high-strength steel sheet is avoided using an unloading stage with return stroke [13].

The kinetic limitations of the servo press mainly due to their own inertia are stated by [25]. In this work, the authors describe four key control points that occur during the slide motion stroke in a regular stamping operation; quick closing of the die, reduction of the slide velocity to soften the impact on the die, and improve the forming quality, retraction from the die, and running at a low speed by the top dead center. An optimization model was developed that maximizes the production rate, considering the boundary conditions of the servo press. However, the motion profiles that include step, vibration, or attach-detach movements are not mentioned. [25]
3.1.5 Bottoming and Re-striking in Bending

For the reduction in the weight of cars, high strength steel sheets tend to be applied to body panels. Due to high strength of these sheets, the amount of springback in bending becomes remarkably large, and thus the dimensional accuracy of formed products deteriorates. To reduce the springback, controlled ram motion in V-shaped bending of various high strength steel sheets (Figure 21) was used. The amount of springback for a 980MPa level ultra-high strength steel sheet was considerably reduced by the bottoming, whereas the amount was hardly improved by holding at the bottom dead center as shown in Figure 22. The stress distribution in the bent sheet was changed by bottoming. The effect of the forming speed on springback in the bending of the ultra - high strength steel sheet is small. [23]

Figure 21 : Ram Motions for reducing springback in bending of sheet metal  [21]
Figure 22: Reduction in springback by bottoming in V-shaped bending of 980MPa level ultra–high strength steel sheet [21]

[27] employed re-striking to eliminate the springback and twisting in U-shaped bending. In the 1st strike, both flanges are bent into a large corner radius and both corners are sharply shaped in the 2nd strike. By optimizing the ram motion in the servo press, the two strikes are included in one stage, whereas this product is generally formed by two stages.
3.2 Material Properties / Lubrication

3.2.1 Determination of material properties by the uniaxial tensile test

The standard uniaxial tensile test is commonly used to determine the mechanical properties of the sheet materials. The standard size specimen and dimensions are shown in Figure 24.

Figure 24: Tensile test specimen according to ASTM E8/E8M-09 [18]
In the uniaxial tensile test, the standard specimen is placed in a tension-test machine. The two ends of the specimen are gripped to ensure that specimen is held straight during the test as shown in Figure 25. An extensometer is attached to the specimen to measure the elongation over an original gage length as shown in Figure 24. The load cell is used to measure the force applied on the specimen at any instant. After the force and elongation are recorded in the data acquisition system, the various material properties diagrams can be created. The procedure of estimation of the flow stress curve using tensile test is described in detail in CPF report 2.1/12/02 [33]. Modern tensile test machines use Digital Camera Systems, instead of extensometers, to determine the local strains in the tensile specimen during the test. [18]

Figure 25: Set up for tensile test [33]
Limitations of the tensile test:

Uniaxial state of stress

- The tensile test only provides ductility and work hardening under uniaxial tension conditions. This deformation condition does not represent the material behavior in unequal biaxial stretching that usually occurs in practical sheet metal forming operations. Therefore, it is necessary to test the material under biaxial deformation conditions using the biaxial bulge tests. [18]

Limited strain range

- The flow stress curve obtained from the tensile test is limited to the point at which local necking is observed. This maximum strain at local necking is small compared to the strains encountered in actual stamping operations.

- Sheet material properties (flow stress data) for the parts undergoing large deformations (large strains) are critical to the accuracy of predictions. Extrapolation of flow stress data from the tensile test to large strains is an approximation and not necessarily accurate.

- In the biaxial bulge test, the maximum effective strain achievable without local necking is much larger (usually twice) than that in the tensile test. Therefore, flow stress curves obtained from the biaxial bulge test are over a larger strain range, compared to the tensile test. [18]
3.2.2 Determination of material properties by the viscous pressure bulge (VPB) test

In the bulge test, the sheet metal clamped at its edges is stretched against the circular die using viscous medium, as shown in Figure 26. The sheet metal bulges into a hemispherical dome and eventually it bursts.

The tooling is usually designed for a single action hydraulic press that uses a punch to pressurize the viscous medium (see Figure 27). The upper die is connected to the slide of the press and the lower die is connected to the cushion of the press. The punch in the lower die is fixed to the press table. At the beginning, the tooling is open and the blank sheet is placed between the upper and the lower dies. Then the dies close to clamp the blank material and the slides moves down together with the entire die set. Consequently, the viscous medium is pressurized by the stationery punch and the sheet is bulged by the viscous medium flowing into the upper die as shown in Figure 27.

![Diagram of the bulge test](image)

Figure 26: geometry before and after the test (\(t_0 = \) origical sheet thickness, \(t_d = \) sheet thickness at the apex, \(h_d = \) bulge neight, \(P = \) hydraulic pressure, \(r_c = \) die fillet radius, \(d_c = \) die cavity diameter, \(r_d = \) radius of curvature) [30]
3.2.3 Tests for evaluation of lubricants

Various tribological tests are used to evaluate the performance of lubricants under laboratory conditions such as cup drawing test (CDT) and limiting dome height (LDH) test:

- Cup drawing test can emulate the production conditions such as contact pressure and speed
- Limiting dome height (LDH) can evaluate the friction condition between punch and sheet, by observing the location of the fracture point
3.2.3.1 Cup drawing test (CDT)

In the cup drawing test, a hollow part is formed by forcing a flat, circular blank into a die using a punch (see Figure 28). The initial blank is constrained by the blank holder, while central portion of the sheet is pushed into a die opening with a punch, to draw the metal into the desired shape without causing wrinkles or splits in the drawn part. Figure 29 shows the schematic of CDT tooling developed by CPF. [18]

Figure 28: Schematic of cup drawing [10]
Performance evaluation criteria for cup drawing test include:

- Maximum drawing load attained (The lower the force, the better the lubrication condition)
- Maximum applicable blank holder force (BHF) without failure of the cup (The higher BHF that is applied without fracture in the drawn cup, the better the lubrication condition)
- The measurement of draw-in length, $L_d$, and perimeter of flange in a drawn cup (The larger the draw-in length or smaller the perimeter, the better the lubrication condition)

Using FE simulations and inverse analysis, it is possible to determine the coefficient of friction (COF) for input into FE simulation.
3.2.3.2 Limiting dome height test (LDT)

The LDT test, Figure 30, is used to evaluate lubricants and assess the formability of the materials in industry. This test consists of stretching a sheet metal over a hemispherical punch while the blank is held between lock beads to prevent ‘draw-in’. Dome test is similar to VPB test. However, this test uses hemispherical solid punch for forming the blank instead of viscous medium used in VPC test. Therefore, friction at tool – work piece interface influences formability and thinning distribution. As friction increases, maximum thinning location moves toward die corner radius as shown in Figure 31. The various lubricants can be evaluated by observing the location of fracture on the sheet sample. A good lubricant such as Teflon or wax can be used to achieve maximum thinning at or very near to the apex of the dome.

The LDT can also be used to evaluate lubricants and to determine the COF. However, the reproducibility and accuracy of the test results are usually not satisfactory.
Figure 30: Schematic of limit dome height test [32]

Figure 31: Change in the location of maximum thinning with increased COF [32]
4.1 Objectives and Approach

4.1.1 Objective

The objective of the present work is to determine how to improve the forming process (better part quality, increased draw depth and reduced material) using a programmable CNC servo-cushion in a servo drive press, using Hyson die geometry shown in Figure 32.

The overall dimensions of the Hyson part are shown in Figure 33.

![Hyson Die Geometry](image)

Figure 32: Hyson Die Geometry
4.1.2 Approach

To achieve the above-mentioned objectives, the following approach is used

- Develop 3-D simulation model of Hyson geometry using PAMSTAMP-3D
- Determination of a criterion for prediction of wrinkles
- Investigation of a methodology to determine optimum variable blank holder force
- Develop the optimum variable blank holder force curve using the methodology
- Comparison between variable, constant BHF and simulation with spacer to see effectiveness of variable blank holder force
- Experiments at Hyson using the variable blank holder force and ‘Attach-Detach’
- Evaluation of experiment samples based on draw-in and thickness distribution for evaluation of better part quality.
4.2 Finite Element Simulations

4.2.1 Criterion for prediction of wrinkles

Wrinkling is affected by many factors, such as process parameters, contact condition, mechanical properties, and geometry of the blank. The flange wrinkles were detected using a geometry based wrinkle detection technique. They are determined by measuring the distance between the two points as shown in Figure 34.

![Figure 34: Method of measuring wrinkles in simulation](image)

\[
\text{Height of wrinkle} = \frac{x}{t} \times 100
\]

Where \( x \) = height of wrinkle, \( t \) = initial thickness of blank

The wrinkle height may be selected based on part geometry, material and blank thickness. In this case, it should be less than 1% of initial blank thickness, \( t \) (\( t=1\text{mm} \)). The wrinkles were measured at two different planes in the simulation. The planes were taken at a distance close to the flange so that wrinkles can be measured more accurately and precisely. Plane A is at a distance of 63mm from origin in \( x \)-direction and Plane B is at a distance of 57mm from origin in \( y \) direction as shown in Figure 35.
4.2.2 Determination of optimum blank holder force

FE simulation to predict optimum variable blank holder force has been coupled with the methodology shown in Figure 36. The main objective is to develop variable blank holder force just required to suppress wrinkle throughout the stroke with minimum thinning in the part. The blank holder force is adjusted at the desired time step during the FE simulation based on the knowledge of the wrinkles in the part in the previous step such that, the wrinkles in the flange can be maintained below a desired value.
Figure 36: Flow chart of methodology to determine optimum blank holder force
4.2.3 Simulation of Hyson part geometry

4.2.3.1 Input parameters in the simulation

The geometry of the Hyson die and dimensions of Hyson part is shown in Figure 32 and Figure 33. A circular blank, 190mm diameter is used. The input parameters in the simulation and flow curve are shown in Table 1 and Figure 37.

Table 1 : Input parameters in the simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (t)</th>
<th>COF</th>
<th>Punch Speed</th>
<th>Total Punch Stroke</th>
<th>Flow Stress Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS304</td>
<td>1mm</td>
<td>0.1</td>
<td>10mm/s</td>
<td>70mm</td>
<td>CPF bulge test data</td>
</tr>
</tbody>
</table>
Figure 37: Flow stress curve obtained from bulge test conducted at CPF

The flow stress data is obtained from bulge test (conducted at CPF) is for 0.86mm SS304 (CPF Report: 1.1/06/03)
4.2.3.2 Simulation with Spacer

To learn from spacer concept (drawing when using spacers) to derive optimum blank holder force versus stroke, simulation has been run to determine the minimum reaction force on binder (sheet) when spacers are used. Spacer with distance 15% more than initial blank thickness is used. The load applied on the blank from the blank holder is shown in Figure 38.

Figure 38: Flow curve of load applied on blank from blank holder in simulation with spacer
4.2.3.3 Simulation with Variable and Constant Blank Holder Force (without spacers)

The methodology used to obtain the variable blank holder force is shown in Figure 36. The optimum variable blank holder force obtained from using the methodology is shown in Figure 39. The wrinkles obtained from the variable blank holder force used are less than 1% of the initial blank thickness in the entire forming stroke. The blank holder force has been increased at that stroke where wrinkles increase more than 1% of initial blank thickness. As the maximum blank holder force required to prevent wrinkles less than 1% is 140 KN in variable blank holder force curve (Figure 39), simulation with constant blank holder force of 140 KN is run to compare it with the results obtained from variable blank holder force.

![Flow curve of variable blank holder force](image)

Figure 39: Flow curve of variable blank holder force obtained using the methodology in Figure 36
4.2.4 Comparison of simulation results (variable and constant BHF and simulation with spacer)

Based on the simulation results obtained, comparison between variable, constant blank holder force and simulation with spacer has been made based on below points:

4.2.4.1 The location of maximum thinning obtained from simulation

Simulation results show maximum thinning is at the same location, at the top of the part for 70mm drawn depth as shown in Figure 40. The value of maximum thinning obtained from simulations for different cases is shown in Table 2. Maximum thinning at 70mm stroke is less in case of variable blank holder force than constant blank holder force and using spacers.

Figure 40: Maximum thinning location obtained from simulations
Table 2: Different cases and value of maximum thinning obtained from simulations

<table>
<thead>
<tr>
<th>Case</th>
<th>BHF</th>
<th>Maximum thinning at 70 mm stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spacer used–1.15t</td>
<td>30.7%</td>
</tr>
<tr>
<td>2</td>
<td>Variable (no spacer) (Figure 39)</td>
<td>29.2%</td>
</tr>
<tr>
<td>3</td>
<td>Constant (no spacer) 140KN</td>
<td>30.8%</td>
</tr>
</tbody>
</table>

4.2.4.2 Comparison of wrinkle heights obtained from simulation

Simulation using PAM-STAMP 3D has been carried out by considering the three cases shown in Table 2. The wrinkles obtained from different simulations have been compared. The maximum drawing height of the part is 70mm. However, the flange at 70mm stroke is near the die corner radius. So, the wrinkles are calculated at 60mm stroke and are shown in Table 3. Hyson blank geometry (circular blank, diameter 190mm) is used in all the simulations. The definition of wrinkle height and the location of Planes A and B are described in Figure 34 and Figure 35.
Table 3: Comparison of wrinkle heights obtained from simulations

<table>
<thead>
<tr>
<th>Case</th>
<th>Stroke</th>
<th>Blank holder force</th>
<th>Wrinkles Plane A (% of t)</th>
<th>Wrinkles Plane B (% of t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60mm</td>
<td>Spacer used-1.15t</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>2</td>
<td>60mm</td>
<td>Variable (Figure 11) (no spacer)</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>60mm</td>
<td>Constant 140KN (no spacer)</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The wrinkle appearance on the part in the simulation is shown in Figure 41.

Figure 41: Wrinkle comparison on part for different cases

From Table 3 and Figure 41 wrinkle height is less in case of variable blank holder force and constant blank holder force.
4.2.4.3 Comparison of Stroke versus Thinning

The stroke versus thinning comparison for the 3 cases are shown in Figure 42.

![Graph showing comparison of stroke versus thinning](image)

Figure 42: Stroke versus thinning comparison for different cases

4.2.4.4 Comparison of Thinning Distribution

As seen from Figure 42, the thinning difference between the different cases is maximum at stroke 40mm; the thinning distribution is compared at that stroke. Figure 43 shows the comparison of thinning distribution obtained from variable and constant blank holder force (no spacers) and Figure 44 shows the comparison of thinning distribution obtained from variable blank holder force and using spacers. Thinning distribution on the part is significantly less in case of variable blank holder force than constant blank holder force.
Figure 43: Comparison of thinning distribution obtained from variable and constant BHF (no spacers)

Figure 44: Comparison of thinning distribution obtained from variable BHF and using spacers
4.2.4.5 Results of simulations (with and without spacer)

- In using variable BHF without spacers (compared to constant BHF=140KN)
  - There are less wrinkles
  - The maximum thinning and thinning distribution is less
- As expected, in using spacers there are more wrinkles and the maximum thinning is higher.
4.2.5 Comparison of variable BHF predicted by CPF and Hyson BHF (without spacers)

4.2.5.1 Variable BHF used by Hyson and CPF

The variable blank holder force derived by Hyson is compared with variable blank holder force obtained by CPF. The comparison is shown in Figure 45.

Figure 45: Comparison of Hyson variable blank holder force verses CPF variable blank holder force

Simulation with PAMSTAMP 3D has been carried out by using Hyson variable blank holder force shown in Figure 45. The results obtained have been compared with results obtained from CPF variable blank holder force simulation.
4.2.5.2 Comparison between stroke versus thinning

Figure 46 shows the stroke versus thinning comparison obtained from simulation results of Hyson variable blank holder force and CPF variable BHF.

Figure 46: Stroke versus thinning comparison
4.2.5.3 Comparison of wrinkle height obtained from simulations

The wrinkles obtained from simulations have been compared. The maximum drawing height of the part is 70mm. However, the flange at 70mm stroke is near the die corner radius. So, the wrinkles are calculated at 60mm stroke and are shown in Table 4. Hyson blank geometry (circular blank, diameter 190mm) is used in all the simulations. The definition of wrinkle height and the location of Planes A and B are described in Figure 34 and Figure 35.

Table 4: Comparison of wrinkle heights obtained from simulation

<table>
<thead>
<tr>
<th>Case</th>
<th>Stroke</th>
<th>Variable</th>
<th>Wrinkles Plane A (% of t)</th>
<th>Wrinkles Plane B (% of t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60mm</td>
<td>Hyson</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>60mm</td>
<td>CPF</td>
<td>1</td>
<td>0.8</td>
</tr>
</tbody>
</table>
4.2.5.4 Discussions

- The Hyson variable blank holder force is very different from CPF obtained variable blank holder force.
- The maximum thinning obtained from Hyson variable blank holder force is 1% less than the maximum thinning obtained from CPF variable blank holder force from simulations.
- The wrinkle on the part with Hyson variable blank holder force is more than CPF variable blank holder force.
- These results indicate that similar thinning values can be obtained by using considerably different BHF versus stroke curves.
4.2.6 Comparison of simulation results with Hyson part without spacers (validation)

4.2.6.1 Preliminary Comparison (Hyson Part/CPF simulations)

To be able to compare experimental results with simulation results, thickness distribution of the Hyson part was measured. Thickness measurement of one sample has been done. The input conditions given to the press to form the part is not known.

The sample was cut through the location of maximum thinning obtained from simulation for measurement, so that the maximum thinning in the part can be measured and compared. Figure 47 shows the location of section in simulation where maximum thinning is obtained and Figure 48 shows the photo of cut sample through the location of maximum thinning.

Figure 47: Location of section in simulation where maximum thinning is obtained
Figure 48: Photo of cut sample and measurement line shown

The experiment thinning results obtained have been compared with simulation results in Figure 49. The location of data points on the part is shown in Figure 50.
Figure 49: Comparison of experiment thinning results with simulation thinning results

Figure 50: Location of the data points on the Hyson part
4.2.6.2 Discussions

- Thinning prediction at point 4, 5 and 6 is close to what measured in the experiment.
- The location (point 5) and value of maximum thinning in simulation is nearly the same as in experimental sample.
- There is no difference in thinning obtained at points 1, 2 and 3. But we do not know the input conditions used in experiments so it will be hard to compare the predictions with experiment.
4.3 Experimental Investigation (no spacers were used)

Hyson experiments have been carried out by using 300 Ton Komatsu servo press with 50 Ton servo hydraulic cushion (Figure 51) at Hyson.

Figure 51 : Photo of Komatsu Servo Press and tooling at Hyson

Experiments have been carried out by considering two different cases as given below:
4.3.1 Forming with variable and constant blank holder force

Simulations have been carried out to determine the optimum blank holder forces versus stroke curve and to determine the process window for stainless steel. The blank holder force versus time curve obtained has been shown in Figure 52. CPF 2 variable BHF has been derived such that the maximum blank holder force in CPF variable BHF 1 matches with the Hyson variable BHF. The difference between Hyson and CPF BHF is that, the Hyson curve starts with a high BHF and low BHF at the end whereas the CPF curve starts with a low BHF and high at the end. The effect of blank and process variables for constant and variable blankholder force on fracture, wrinkle height and maximum thinning has been studied.

![ CPF and Hyson variable blank holder force curves used in experiments ]

Figure 52: CPF and Hyson variable blank holder force curves used in experiments

The results obtained from the Hyson experiments have been summarized in Table 5 and Figure 53. In these experiments, the ram was stopped before the upper die touches the
sheet (no damage through sheet). The press speed was 11 SPM and no spacers were used in the experiments.

Table 5: Summary of results obtained from variable and constant blank holder force experiments

<table>
<thead>
<tr>
<th>BHF (variable and constant) (Figure 52)</th>
<th>Punch Force [Tons]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Hyson</td>
<td>55</td>
<td>✔ Formed (2 samples)</td>
</tr>
<tr>
<td>Variable CPF 1 (Max.140KN)</td>
<td>66</td>
<td>✔ Necking (3 samples)</td>
</tr>
<tr>
<td>Variable CPF 2 (Max.60KN)</td>
<td>50</td>
<td>✔ Formed (2 samples)</td>
</tr>
<tr>
<td>Constant 30 KN</td>
<td>49</td>
<td>✗ Small wrinkle (2 samples)</td>
</tr>
<tr>
<td>Constant 60 KN</td>
<td>53</td>
<td>✔ Formed (2 samples)</td>
</tr>
<tr>
<td>Constant 140KN</td>
<td>70</td>
<td>✗ Cracked (2 samples)</td>
</tr>
</tbody>
</table>
Figure 53: Summary of results obtained from variable and constant blank holder force experiments.
4.3.2 Forming with Attach-Detach Method and Speed effect

The principle of Attach-Detach has been shown in Figure 54 and Figure 55. The die is drawn to stroke 30mm ‘attach’ and then it is uplifted by 5mm ‘detach’ and again drawn till final stroke to BDC 70mm.

![Punch stroke [mm]](image)

Figure 54: Attach-detach method used

<table>
<thead>
<tr>
<th></th>
<th>0 mm stroke</th>
<th>30 mm stroke</th>
<th>5 mm detach</th>
<th>70 mm final stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Die</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Punch</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 55: Schematic showing attach-detach principle
The results obtained from the experiments have been summarized in Table 6 and Figure 56.

Table 6: Tabular summary of results obtained from attach-detach experiments

<table>
<thead>
<tr>
<th>Test #</th>
<th>BHF (Constant)</th>
<th>Speed [SPM]</th>
<th>Type of Press Motion</th>
<th>Punch Force [Tons]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140KN</td>
<td>11</td>
<td>Stop before touch</td>
<td>70</td>
<td>✗ Cracked (2 samples)</td>
</tr>
<tr>
<td>2</td>
<td>140KN</td>
<td>19</td>
<td>Stop before touch</td>
<td>66</td>
<td>✗ Crack-different location (2 samples)</td>
</tr>
<tr>
<td>3</td>
<td>140KN</td>
<td>12</td>
<td>Attach/Detach Down 30mm-</td>
<td>66</td>
<td>✗ Crack (2 samples)</td>
</tr>
<tr>
<td>4</td>
<td>100KN</td>
<td>12</td>
<td>Attach/Detach Down 30mm-</td>
<td>61</td>
<td>✔ Formed (2 samples)</td>
</tr>
<tr>
<td>5</td>
<td>100KN</td>
<td>12</td>
<td>Stop before touch</td>
<td>63</td>
<td>✗ Crack (3 samples, 2 cracked, 1 necking)</td>
</tr>
<tr>
<td>6</td>
<td>100KN</td>
<td>19</td>
<td>Stop before touch</td>
<td>61</td>
<td>✔ Formed (2 samples)</td>
</tr>
</tbody>
</table>
Figure 56: Schematic of results obtained from attach-detach

Figure 57: Schematic of change in fracture location with different press speeds

From Figure 57, with change in press speed the location of fracture also changes.
4.3.3 Results of experiments

- As expected, in drawing without spacers (with or without variable BHF), with increasing maximum BHF the probability of fracture increases.
- With the CNC Cushion, BHF vs Stroke determined by FE simulation and try-out, can both form this part successfully.
- When at BDC large BHF is required, variable BHF seems to offer advantages.
- Increasing ram speed during deformation and using the “Attach-Detach” method improves drawability. However, additional studies may be needed to define the process conditions quantitatively.
- CNC cushion is very helpful in the determination of “BHF versus stroke curve and Maximum allowable BHF for avoiding fracture"
4.4 Comparison of experimental results with simulations (no spacers)

4.4.1 Measurement of Draw-in

Draw-in in the part was measured as shown in Figure 58. It is assumed that the draw-in is symmetric in negative and positive x and y direction.

![Diagram of Initial blank and draw-in measurements](image)

- **Flange outline after forming**
- **Initial blank (190 mm)**
- **x-direction**
- **y-direction**

\[
\text{Draw-in (x-direction)} = \frac{(190-x)}{2} \\
\text{Draw-in (y-direction)} = \frac{(190-y)}{2}
\]

Figure 58 : Method used to measure draw-in in x and y direction

The experimental results obtained from draw-in measurements in x and y direction are shown in Figure 59 and Figure 60. The different cases in Figure 59 and Figure 60 are given in Table 7. Cases marked with * indicate that the part has been fractured and ** indicate that there are wrinkles in the part in Table 7.
Figure 59: Graph of results obtained from draw-in measurements in x direction

Table 7: Details of different cases

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2*</th>
<th>3</th>
<th>4**</th>
<th>5</th>
<th>6*</th>
<th>7*</th>
<th>8*</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHF(KN)</td>
<td>60</td>
<td>140</td>
<td>60</td>
<td>30</td>
<td>60</td>
<td>140</td>
<td>140</td>
<td>100</td>
<td>100</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Curve (Fig.24)</td>
<td>Hyso n</td>
<td>CPF</td>
<td>Cons</td>
<td>.</td>
<td>Cons</td>
<td>CPF</td>
<td>Cons</td>
<td>Cons</td>
<td>Cons</td>
<td>A-D</td>
<td>A-D</td>
</tr>
<tr>
<td>Speed (SPM)</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>19</td>
<td>12</td>
<td>19</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>
Figure 60: Graph of results obtained from draw-in measurements in y direction

It can be seen from Figure 59 and Figure 60 that there is 7mm more draw-in with 140KN blank holder force and 2mm more draw-in when the speed is increased from 11SPM to 19SPM. There is increase in draw-in by 2-3mm when using attach-detach. The experimental draw-in measurements are compared with simulation results as shown in Figure 61 and Figure 62. Simulation cannot be run using attach-detach method, so we have comparison results for 1-9 cases in Figure 61 and Figure 62.
Figure 61: Comparison of experimental and simulation results obtained from draw-in measurements in x direction

Figure 62: Comparison of experimental and simulation results obtained from draw-in measurements in y direction
There is considerable difference in simulation and experimental draw-in measurements. Also, the draw-in measured from simulations does not show significant difference with change in speed but there is small difference in draw-in with change in BHF.

4.4.2 Measurement of thickness distribution

The thickness of the formed part was measured at the location of maximum thinning as observed in simulations. Several data points were taken as shown in Figure 63 and Figure 64.

Figure 63: Location of points taken on part for thickness measurement
The results obtained from the measurement of thicknesses can be seen in Figure 65.

Figure 64: Location of the data points on the Hyson part

Figure 65: Measurement of thickness distribution in experiment
The experimental results are compared with simulation results. The effect of speed on the simulation and experimental results has been shown in Figure 66.

Figure 66: Thickness distribution comparison of experimental and simulation results

The thinning distribution measured from simulations does not show significant difference with change in speed. There is significant difference in thinning when simulation results are compared with experimental results except for points 4, 5 and 6.
4.5 Comparison of target BHF (input to press) versus actual BHF (output/measured from the press)

Figure 67 shows the comparison of target BHF (input to the press) versus actual BHF (output/measured from the press)

![Graph showing comparison of target BHF (input) versus actual BHF (output).]

Figure 67: Comparison of Target cushion BHF (input to the press) versus actual cushion BHF (output/measured from the press)

It can be seen from Figure 67 that target BHF (input to the press) does not match with actual BHF (measured/output from the press) due to system inertia. Also, changing the target force from 27000 pounds (120KN) to 15000 pounds (66KN) takes 7mm of stroke.

In Figure 68 and Figure 69, target and actual BHF versus time curve has been shown for
two different cases: A.) Simulation with constant 100KN BHF and ram speed 11SPM and B.) Simulation with constant 100KN BHF and ram speed 19 SPM. The effect of ram speed on the target BHF (input to the press) and actual cushion (output/measured from the press) has been studied.

Figure 68: Comparison of Target blank holder force versus actual blank holder force for 100KN BHF and ram speed of 11SPM.
Figure 69: Comparison of Target blank holder force versus actual blank holder force for 100KN BHF and ram speed of 19SPM.

From Figure 68 and Figure 69, increasing the ram speed leads to overshoot.
4.6 Summary and Conclusions

The objective of the study, discussed in this report, was to investigate the improvement of stamping operations using a CNC hydraulic servo-cushion.

4.6.1 Summary

1. One forming example was studied: (1) Deep Drawing of Hyson die using SS304,1mm material

2. The criterion to be used for wrinkle detection were determined and a methodology to determine variable blank holder force was investigated.

3. FE model was developed to obtain variable blank holder force using the methodology. The variable blank holder force was compared with constant blank holder force and simulation with spacer based on thinning, wrinkles and thinning distribution obtained from FE simulations.

4. The simulation predictions with variable blank holder force were compared with experiments conducted at Hyson. The variable blank holder force curve obtained by Hyson was compared with variable blank holder force curve obtained by CPF.

5. Experiments were conducted by using 300 Ton Komatsu servo press with 50 Ton servo hydraulic cushion at Hyson. Experiment results were compared with simulation results based on draw-in, thickness measurement and cushion force.
4.6.2 Conclusions

This study illustrated that

- Better results (less thinning and wrinkles) can be obtained by using a variable blank holder force than using constant blank holder force and spacers.
- Experimental results show that better part quality (more draw-in) can be obtained by using a variable blank holder force and higher ram speed.
- The thickness distribution in the successfully drawn parts is almost the same for all press and cushion motions, except for the fractured part.
- The target cushion force (input to the press) does not match with actual cushion force (measured/output from press) due to system inertia.
- With 100kN blank holder force, increasing ram speed (from 12SPM to 19SPM) during deformation and using the “Attach-Detach” method improves drawability. The possible reasons for improving drawability when using “Attach-Detach” are:
  - The change of contact condition due to springback. After the detach, the contact condition of the blank and tools can be changed due to springback on the part.
  - The attach detach can change the lubrication conditions. The coefficient of friction can be approximately reduced by 0.005 due to attach/detach.
  - The strain release may affect the forming process.
5.1 Objectives and Approach

5.1.1 Objectives

The objective of the present study is to determine using the Hyson Die, the optimum blank geometry using Steel A1008 CRS Type B material (thickness – 1mm). Also, determine whether the draw depth can be increased by using pulsating blank holder force.

The overall dimensions of the Hyson part are shown in Figure 32 and Figure 33

5.1.2 Approach

To achieve the above objectives, the following approach is used

- Develop 3-D simulation model of Hyson geometry using PAMSTAMP 3D
- Compare simulation results with forming limit diagram to determine whether the part could be formed
- Experiments at Hyson using constant blank holder force to determine optimum blank geometry
- Experiments with pulsating blank holder force using the optimum blank geometry to determine whether the draw depth could be increased
5.2 Finite Element Simulations using PAMSTAMP 3D

5.2.1 Input parameters in the simulation

The geometry of the Hyson die and dimensions are shown in Figure 32 and Figure 33. A circular blank, 190mm diameter is chosen for simulations with Steel A1008 CRS Type B material as prior experiments have been conducted with 190mm diameter with Stainless Steel 304 material and formed successfully till 70mm draw depth. The input parameters in the simulation and flow curve are shown in Table 8 and Figure 70. The flow stress data is obtained from tensile test (conducted at CPF) for Steel A1008 CRS Type B, 1mm thickness. The simulation results will be compared with forming limit diagram from PAMSTAMP. The initial blank holder force to be used in simulations is calculated from the formulae shown in Figure 71.
Table 8: Input data to simulation

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Steel A1008 CRS Type B</td>
</tr>
<tr>
<td>Tool description</td>
<td>Punch, blank holder and the upper die are assumed as rigid bodies</td>
</tr>
<tr>
<td>Thickness (t)</td>
<td>1mm</td>
</tr>
<tr>
<td>Flow Stress data</td>
<td>Tensile test conducted at CPF</td>
</tr>
<tr>
<td>Blank holder force</td>
<td>10kN</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.1</td>
</tr>
<tr>
<td>Blank geometry</td>
<td>Diameter 190mm</td>
</tr>
</tbody>
</table>

Figure 70: Flow Stress curve used in simulations for Steel A1008 CRS Type B, 1mm

[Tensile test has been conducted at CPF]
Figure 71: Formulae used for calculation of initial blank holder force [1]

\[
p_{BH} = 10^{-3} c \left[ (DR - 1)^3 + \frac{0.005d_0}{s_0} \right] S_u
\]

\[
F_{BH} = p_{BH} \times A_{BH}
\]

where:
- \( s_0 \) is the blank thickness
- \( d_0 \) is the blank diameter
- \( p_{BH} \) is the blankholder pressure
- \( F_{BH} \) is the blankholder force, BHF
- \( A_{BH} \) is the area of the blank under the blankholder
- \( c \) is the empirical factor, ranging from 2 to 3
- \( S_u \) is the ultimate tensile strength of the sheet material
- \( DR \) is the draw ratio (blank diameter/cup diameter)

5.2.2 Simulation with constant blank holder force and comparison with forming limit diagram

Simulation using PAMSTAMP 3D has been conducted by using the input data shown in Table 8 and flow curve shown in Figure 70. The maximum thinning and location of maximum thinning obtained from simulations has been shown in Figure 72. Simulation results has been compared with forming limit diagram to determine whether the part will be formed (Figure 73). Using 10kN blank holder force the part does not crack after
comparing it with forming limit diagram. PAMSTAMP forming limit diagram has been used.

Figure 72: Maximum thinning and thinning location in simulations with Steel A1008 CRS Type B material

Figure 73: Comparison of simulation results with forming limit diagram
5.3 Experimental Investigation (no spacers were used)

Hyson experiments have been carried out by using the 300 Ton Komatsu servo press with 50 Ton servo hydraulic cushion (Figure 51) at Hyson. Experiments have been carried out considering different cases as given below:

5.3.1 Forming with constant blank holder force to obtain optimum blank geometry

Simulations have been carried out to determine the optimum blank holder force required to form the part. As per the simulations results, experiments were performed with 10kN constant blank holder force and it has been observed that part has been cracked. As the part cracked, blank geometry was modified to obtain optimum blank geometry which can form part to maximum draw depth. Using 10kN constant blank holder force it has been observed that the part has been cracked at 35mm draw depth and the target draw depth was 70mm. The different blank geometries tested are given in Figure 74 and the results of the tests with different blank geometries are given in Table 9. Blank Shape D is the optimized blank shape and the maximum draw depth that can be achieved is 60mm using Steel A1008 CRS Type B, 1mm material. Using 85kN constant blank holder force, it has been observed that one sample cracked while one samples was formed. By trimming the blank on four sides by 5mm, draw depth could be increased by 70% as shown in Figure 75.
Figure 74: Different blank geometries tested in experiments
Table 9: Results obtained with different blank geometries

<table>
<thead>
<tr>
<th>Blank Shape</th>
<th>Target draw depth</th>
<th>BHF used</th>
<th>Comment</th>
<th>Next Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70mm</td>
<td>10KN</td>
<td>Blank cracked at 35mm draw depth</td>
<td>Reduce the blank size to form the part up to 35mm draw depth</td>
</tr>
<tr>
<td>B</td>
<td>35mm</td>
<td>5kN to 20kN</td>
<td>Blank formed up to 35mm draw depth but there was no flange remaining to increase the draw depth</td>
<td>Increase the blank size so that part can be formed deeper</td>
</tr>
<tr>
<td>C</td>
<td>40mm</td>
<td>20kN to 110kN</td>
<td>Part formed up to 40mm draw depth but there was no flange remaining to increase the draw depth</td>
<td>Increase the blank size so that part can be formed deeper</td>
</tr>
<tr>
<td>D (optimized)</td>
<td>60mm</td>
<td>50kN to 75kN</td>
<td>Part formed up to 60mm draw depth.</td>
<td>This is the maximum draw depth that can be achieved</td>
</tr>
</tbody>
</table>
5.3.2 Forming with pulsating blank holder force

It can be seen from previous section that by using 85kN constant blank holder force, one sample was cracked while one sample was formed. Experiments were conducted using pulsating blank holder force to determine whether draw depth can be increased. Results obtained from experiments conducted with pulsating blank holder force have been shown in Table 10. By using amplitude 85kN to 20kN and frequency 5hertz/sec and 15hertz/sec, all samples were formed (2 per test). It has been hypothesized that, using pulsating blank holder force reduces the coefficient of friction in the flange. The friction force is directly proportional to the normal force applied on the flange of the blank. Therefore, the effect of pulsation is higher when using high blank holder force.
Table 10: Experimental results with Pulsating blank holder force

<table>
<thead>
<tr>
<th>Condition</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant BHF – 85kN</td>
<td>One sample cracked and one sample formed up to 60mm</td>
</tr>
<tr>
<td>Pulsating BHF</td>
<td></td>
</tr>
<tr>
<td>Amplitude: 85kN to 20kN</td>
<td>Both samples formed up to 60mm</td>
</tr>
<tr>
<td>Frequency: 5 pulses/sec</td>
<td></td>
</tr>
<tr>
<td>Pulsating BHF</td>
<td></td>
</tr>
<tr>
<td>Amplitude: 85kN to 20kN</td>
<td>Both samples formed up to 60mm</td>
</tr>
<tr>
<td>Frequency: 15 pulses/sec</td>
<td></td>
</tr>
</tbody>
</table>

5.4 Comparison of target blank holder force (input to press) versus actual blank holder force (output / measured from the press)

The ram motion that has been used in experiments is shown in Figure 76. The ram motion was slowed down approximately 1mm before the die touches the blank and after forming for 6mm the speed was increased and reached up to 178mm/sec to complete the entire forming.
Figure 76 : Ram motion used in experiments

5.4.1 Cushion Response – Constant blank holder force

The ram motion used is shown in Figure 76. The cushion response when using 50kN constant blank holder force is shown in Figure 77. There is minor fluctuation during start and end of forming.
5.4.2 Cushion Response – Pulsating BHF

The cushion response when using pulsating blank holder force is shown in Figure 78 and Figure 79. It can be seen from Figure 78 that when using amplitude 85kN to 20kN and 5hertz/sec, the output data matches well with input. From Figure 79 when using amplitude 85kN to 20kN and 15hertz/sec, there is difference in the actual blank holder force when compared with target blank holder force. When using 5hertz/sec it could be seen that only 2 pulses could be achieved and when using 15hertz per sec, 9 pulses could be achieved during the forming stage.

Figure 77: Cushion response when using constant 50kN blank holder force
Figure 78: Cushion response when using pulsating blank holder force (Amplitude 85kN to 20kN and frequency 5 hertz/sec)

Figure 79: Cushion response when using pulsating blank holder force (Amplitude 85kN to 20kN and frequency 15 hertz/sec)
5.5 Summary and Conclusions

5.5.1 Summary

1. One forming example was studied: (1) Deep Drawing of Hyson die using Steel A1008 CRS Type B, 1mm material

2. FE model was developed to obtain constant blank holder force required for experiments. Simulation results were compared with forming limit diagram to determine whether the part can be formed

4. Experiments were conducted at Hyson using 300 Ton Komatsu servo press with 50 Ton CNC hydraulic cushion to obtain optimum blank geometry

5. Experiments were conducted using pulsating blank holder force to determine whether the draw depth of the part could be increased

6. The target blank holder force (input to press) given to press was compared with actual blank holder force obtained from press (output from press)

5.5.2 Conclusions

- By slightly modifying the blank geometry, the draw depth was increased by more than 70%

- With Hyson part geometry, for relatively high blank holder force (about 85kN) slight improvements was observed when using pulsating blank holder force

- The friction force is directly proportional to the normal force applied on the flange on the blank. Therefore, the effect of pulsation is higher when using high blank holder force
• Actual blank holder force does not match well the target blank holder force when using pulsating blank holder force (15 pulses/sec)

• The actual blank holder force matches well the target blank holder force when using constant blank holder force
Chapter 6: Deep Drawing with Honda Die – Aluminum Material

6.1 Objectives and Approach

6.1.1 Objectives

The overall objective of this present study is to:

- Determine using the Honda Die (Figure 80), the “best” process conditions in deep drawing Aluminum 5182-O (1.2mm) in a servo press with servo hydraulic cushion with and without spacers
- Determine the advantages/disadvantages of using spacers (or no spacers) and determine how to optimize spacer height
- Determine the possible advantages of the effect of (a) Attach – Detach technique, (b) Pulsating blank holder force (servo cushion) and (c) Variable blank holder force (servo cushion)
- Develop recommendations on how to deep draw Aluminum parts (with or without spacers)
6.1.2 Approach

To achieve the above-mentioned objectives, the following approach is used:

- Develop 3-D simulation model of Honda geometry using PAMSTAMP – 3D
- Evaluation of accuracy of FLD and wrinkle criterion
- Determination of optimum constant blank holder force with and without spacers and effect of spacer height on thinning through simulations
- Determination of parameters of using variable BHF in experiments through simulations
- Experimental tryouts at Hyson using 300 Ton Komatsu Servo Press with 100 ton CNC hydraulic servo cushion
- Comparison of simulation results with experimental results based on maximum thinning

Figure 80: Schematic of Honda Die Tooling
Comparison of target blank holder force (input to press) versus actual blank holder force (output from press)

6.2 FE simulation model of Honda geometry using PAMSTAMP 3D

The FE simulations are conducted using PAMSTAMP 3D. The Honda die is illustrated in Figure 80. The material used is Aluminum 5182-O and the thickness is 1.2mm. The properties were obtained from Honda and flow stress data (combined tensile and bulge test) is shown in Figure 81. The co-efficient of friction assumed in the simulations is 0.1. The maximum draw depth that can be possible using the servo press and CNC hydraulic servo cushion at Hyson is 120mm as (a) The maximum travel of the servo hydraulic cushion is 120mm and (b) Due to the daylight of the press. The shape and dimensions of blank are shown in Figure 84. First, the blank holder force is applied on the blank, then the upper die moves down and draws the blank against the punch and die cavity to form the part. Barlat 2000 yield criteria was used in simulations, to consider the anisotropic effect. The input parameters for Barlat 2000 is obtained from (Carsley et al., 2013) as shown in Table 11.
Table 11: Input parameters for Barlat 2000 yield criteria, obtained from (Carsley et al., 2013)

<table>
<thead>
<tr>
<th></th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
<th>a5</th>
<th>a6</th>
<th>a7</th>
<th>a8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.936033</td>
<td>1.078701</td>
<td>0.966889</td>
<td>1.004853</td>
<td>1.002609</td>
<td>1.016975</td>
<td>1.032625</td>
<td>1.114336</td>
</tr>
</tbody>
</table>

Figure 81: Flow Stress Data (combined tensile and bulge test data) used in simulations

6.2.1 Evaluation of accuracy of forming limit diagram (FLD)

A forming limit diagram, also known as a forming limit curve is used in sheet metal forming for predicting forming behavior of sheet metal. Simulation has been conducted using PAMSTAMP and simulation result has been compared with experimental results to evaluate the accuracy of FLD. The input parameters in the simulation have been given in Table 12. Simulations have been conducted using the same input conditions as in
experiments. Spacers height 1.5mm have been used with 820kN BHF. Since we don’t have our own forming limit curve for this material, the forming limit curve data provided by [Carsley et al, 2013] was used, see Figure 82

Figure 82: Forming limit curve of Al 5182-O, with thickness of 1.1mm, obtained from [Carsley et al, 2013]
The simulation has been conducted and results have been compared with forming limit diagram. Forming limit diagram at 80mm draw depth has been shown in Figure 83. FLD predicts crack at 80mm draw depth, however experimental samples have been formed till 155mm draw depth by Honda. So, the forming limit diagram used is not reliable. The
new criterion for fracture to be used in this study will be 20% thinning in part which has been reported by Honda (by experience) when using Aluminum 5182-O, 1.2mm

Figure 83: Simulation result compared with FLD at 80mm draw depth

6.2.2 Determination of optimum constant blank holder force with and without spacers and effect of spacer height on thinning

Simulations have been conducted with and without spacers to determine the optimum blank holder force required for Honda die and to determine the effect of spacer height on thinning. The input to simulation has been given in Table 12. The different geometries that have been used in simulations are given in Figure 84. In Figure 84, blank shape A has been designed by Honda and they have used in their experimental tryouts, blank geometry B has been modified from Honda design by CPF so that it can be cut easily with the help of shearing machine which is available in CPF and blank geometry C has
been obtained from PAMSTAMP inverse analysis. The optimum blank holder force should be obtained such that the maximum thinning in simulation should be less than 20% (Based on FLD and Honda suggestion)

![Blank Geometries](image)

**Blank Shape A**  
**Blank Shape B**  
**Blank Shape C**

Figure 84: Blank geometries used in simulations

The results of simulations are given in Table 13. The values of maximum thinning increases when the height of spacer is reduced from 1.5mm to 1.4mm. With a lower
spacer height, the pressure on the part is higher and the material will be more restricted to flow into the cavity. Using Blank Shape B and spacer height 1.6mm, the wrinkles enter the die cavity and restrict metal flow. Therefore, the wrinkle height and maximum thinning are very large. By using 350kN constant BHF no spacers & using constant BHF 820kN with spacers (1.5mm) the maximum thinning is less than 20% in all the blank shapes.

Table 13: Results of simulation with and without spacer

<table>
<thead>
<tr>
<th>Case</th>
<th>Constant BHF</th>
<th>Spacer</th>
<th>Blank shape A (Honda blank shape)</th>
<th>Blank shape B (Modified Honda blank shape)</th>
<th>Blank Shape C (PAMSTAMP inverse analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350kN</td>
<td>No</td>
<td>18.9%</td>
<td>19.1%</td>
<td>18.4%</td>
</tr>
<tr>
<td>2</td>
<td>820kN</td>
<td>Yes (Height - 1.5mm)</td>
<td>17.7%</td>
<td>17.1%</td>
<td>15.5%</td>
</tr>
<tr>
<td>3</td>
<td>820kN</td>
<td>Yes (Height - 1.4mm)</td>
<td>20.8%</td>
<td>22%</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Yes (Height - 1.6mm)</td>
<td>16.7%</td>
<td>No result - High wrinkles</td>
<td>-</td>
</tr>
</tbody>
</table>

102
The flange shape at 120mm draw depth for different geometries has been shown in Figure 87. Flange shape obtained from PAMSTAMP inverse analysis provides more uniform shape. The simulation results with 350KN constant blank holder force without spacers with different blank geometries have been shown in Figure 85 and the maximum thinning location in simulations is shown in Figure 86. From simulation results when using spacers (Height – 1.4mm, 1.5mm and 1.6mm) and 820kN blank holder force, there is no separation between the blank holder and the die (applied blank holder force is enough to maintain the gap between blank holder and die).

Figure 85 : Simulation results using no spacers and 350kN constant blank holder force with different geometries
Figure 86: Maximum thinning location in simulations (Blank shape B)

Figure 87: Flange shape at 120mm draw depth for different blank geometries
6.2.3 Determination of parameters of using variable BHF

To learn from spacer concept (drawing when using spacers) to derive optimum blank holder force versus stroke, simulation has been conducted to determine the minimum reaction force on binder (sheet) when spacers are used. As seen from Table 13, minimum thinning has been obtained when using spacer height 1.5mm (25% more than initial blank thickness), so the load applied on the blank by the blank holder is studied and shown in Figure 88. During deep drawing the flange of the blank becomes thicker and exerts a force on the blank holder. Therefore, the load applied on the blank holder increases with stroke.

Figure 88: Load applied on the blank holder by the blank when using spacers
6.2.4 Results of simulations

- Blank shape C (Figure 84) provides more uniform flange and less maximum thinning, compared to other blank shapes
- Blank shape B, which is similar to that used by Honda will be considered for experiments
- Effect of blank geometry on thinning is more significant in case of using spacers (Table 13)
- Worse results are obtained by using no spacers (350kN) than using spacers (25% thicker than initial blank thickness & 820kN BHF) with different blank geometries (Table 13)
- Using spacers (1.5mm - 25% thicker than initial blank thickness) gives better results (less thinning) than other spacer heights (1.4mm & 1.6mm)

6.3 Experimental set up and samples preparation

Experiments have been carried out by using 300 Ton Komatsu servo press with 100 Ton servo hydraulic cushion at Hyson (Figure 89). The Honda die mounted inside the servo press at Hyson has been shown in Figure 90.
Figure 89: Photo of 300 Ton Komatsu servo press with 100 Ton CNC hydraulic cushion at Hyson
6.3.1 preparation of initial blanks and tool set up

The material required for tests were obtained from Honda. Rectangular Aluminum 5182-O, 1.2mm which were coated with dry lube were obtained. The blank size which were required for experiments were prepared at CPF. Blank shape A was designed by Honda & blank shape C was determined through PAMSTAMP inverse analyses. Blank shapes A & C were cut by using water jet from sheet which was 1000mm*720mm. Blank shape B which was modified from Honda blank design were cut by using shearing machine at CPF. The blank which were applied with dry lube were cleaned with paper towels to remove dust particles. All samples were lubricated by 080-00B lubricant which was
obtained from IRMCO. Also, the original blank thickness was measured before the experiments to reduce error.

While setting up the tooling, the tools were cleaned using paper towel and lubricant was applied on the tools before the start of tests. The clearance between the punch and die were measured using lead wire to make sure the tool clearance is uniform. Lead wires were located on the punch as shown in Figure 91. The diameters of lead wires mounted on the punch were more than the clearance between punch and die. The die was moved down so that the lead wires were squeezed and the exact clearance at different position of the tool can be measured. The lead wires were measured by micrometer and readings were recorded. The exact positions where clearance has been measured is shown in Figure 92 and the clearance values measured are given in
Table 14.

Figure 91: Lead wires located on punch to measure the clearance between punch and die

Figure 92: Positions where clearance between punch and die were measured
Table 14: Clearance values measured at different locations measured between punch and die

<table>
<thead>
<tr>
<th>Positions Measured</th>
<th>Clearance in inches</th>
<th>Clearance in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.065</td>
<td>1.65</td>
</tr>
<tr>
<td>2</td>
<td>0.062</td>
<td>1.57</td>
</tr>
<tr>
<td>3</td>
<td>0.065</td>
<td>1.65</td>
</tr>
<tr>
<td>4</td>
<td>0.064</td>
<td>1.63</td>
</tr>
<tr>
<td>5</td>
<td>0.064</td>
<td>1.63</td>
</tr>
<tr>
<td>6</td>
<td>0.061</td>
<td>1.55</td>
</tr>
<tr>
<td>7</td>
<td>0.063</td>
<td>1.6</td>
</tr>
<tr>
<td>8</td>
<td>0.058</td>
<td>1.47</td>
</tr>
<tr>
<td>9</td>
<td>0.058</td>
<td>1.47</td>
</tr>
<tr>
<td>10</td>
<td>0.058</td>
<td>1.47</td>
</tr>
<tr>
<td>11</td>
<td>0.058</td>
<td>1.47</td>
</tr>
</tbody>
</table>

Preliminary experiments were conducted with dry lube (samples applied with dry lube were stored more than a year) and as expected, all samples cracked. Experiments with Dry + IRMCO lube have been conducted by considering different cases as shown below. 2 samples were used for each test condition.
6.3.2 Forming with and without spacers (geometry B)

Simulations have been conducted to determine the blank holder force to be used in experiments with and without spacers. Depending on simulation results, experiments have been performed. Experimental results when forming with and without spacers when using constant and variable blank holder force is shown in Figure 93.

![Diagram showing experimental results](image_url)

Figure 93: Experimental results when forming with and without spacers using constant and variable blank holder force

Samples have been formed without spacers when using 350kN to 550kN blank holder force and variable blank holder force (Figure 95) and no wrinkles have been observed in part. However, when using spacers (Height 1.4mm and 1.5mm and 550kN BHF), the wrinkles enter the die cavity when the samples were formed as shown in Figure 94.
Schematic diagram of locations where spacers were used and actual location of spacers in experiments has been shown in Figure 96 and Figure 97

Figure 94: (A) Wrinkles entering the die when forming with spacers (B) less wrinkles observed when forming without spacers and using constant and variable blank holder force
Figure 95: Variable blank holder force used in experiments

Figure 96: Schematic of spacers locations used in experiments
6.3.3 Forming without spacers (blank geometry A & C)

Experiments were conducted with blank geometries A & C without spacers and using constant and variable blank holder force. The target draw depth was 120mm.

Experimental results have been shown in Table 15
Table 15: Experimental results when forming without spacers using blank geometry A & C

<table>
<thead>
<tr>
<th>Tests</th>
<th>Blank Geometry</th>
<th>Blank holder force</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B – Honda modified blank geometry</td>
<td>Constant BHF 550kN</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Variable BHF 2</td>
<td>All samples formed</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C – PAMSTAMP modified geometry</td>
<td>Constant BHF 550kN</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Variable BHF 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As seen in Table 15, all parts were formed when using constant and variable BHF without spacers. It can be seen from Figure 98, that improvement in blank shape/size can be obtained by using PAMSTAMP inverse analysis geometry. There was no significant difference is wrinkles measured when using constant and variable blank holder force. Minor wrinkles were observed which did not enter the die cavity.
Figure 98: Improvement in blank shape/size obtained when using PAMSTAMP inverse analysis

6.3.4 Results of experiments

- For the Honda part geometry, using Dry + IRMCO lube all samples (2 per test) were formed till 120mm draw depth
- Better part quality (less wrinkles) can be achieved by deep drawing without spacers and constant blank holder force than deep drawing with spacers
- Improved blank shape/size can be obtained by using PAMSTAMP
• Using Dry + IRMCO lube, experiments were not conducted with servo characteristics (Attach-Detach & pulsating BHF) as all samples were formed using constant BHF (with and without spacers) and variable BHF
• Parts were formed successfully when deep drawing with constant and variable BHF. There is no significant difference when wrinkles were measured in formed samples.

6.4 Comparison of simulation results with experimental tryouts

6.4.1 Based on maximum thinning
Simulation results have been compared with experimental results based on maximum thinning. Preliminary experiments were conducted with dry lube (samples applied with dry lube were stored more than a year) and as expected, all samples cracked. The maximum thinning was measured in the cracked samples and compared with simulation results as shown in Figure 99. The coefficient of friction assumed for the cracked samples was 0.10. All samples which were applied with Dry + IRMCO lubricant were formed. The samples which were formed have been cut at the location of maximum thinning as shown in simulations and maximum thinning in the part has been measured. The coefficient of friction assumed for samples which were applied with Dry + IRMCO lube is 0.07. The location of samples cut have been shown in Figure 100. Experimental tests which were conducted with 350kN constant blank holder force using blank geometry B without spacers have been chosen for comparison with simulations.
It can be seen from Figure 99, when using coefficient of friction 0.10 and 0.07 when using dry lube and Dry + IRMCO lube, the experimental results agree well with simulation results.

Figure 99: Comparison of simulation and experimental results based on maximum thinning
6.5 Comparison of target BHF (input to press) versus actual BHF (output / measured from press)

6.5.1 Ram motion used

The ram motion used in experiments is shown in Figure 101. The ram was slowed down to 10% of maximum possible speed approximately 2mm before die touches the blank and after forming for 6mm the speed was increased to 70% of maximum possible speed to complete the entire forming as shown in Figure 101.

Figure 100: Location of samples cut for measurement of maximum thinning in experiments
Figure 101: (A) Ram slowed down motion when die touches the blank (B) Ram motion during the entire stroke

6.5.2 Servo Cushion response – Constant BHF

The ram motion used in the experiments is shown in Figure 101. The servo cushion response when using constant blank holder force 350kN is shown in Figure 102. There is small fluctuation in blank holder force (actual) during start of forming and end of forming. Ram (or slide) motion can significantly affect the cushion response, specifically when the die starts to touch the material. To provide the best cushion response the die should touch the material as slow as possible and then the speed should be increased to maintain the required cycle time.
Figure 102: Servo cushion response when using constant 350 KN blank holder force
6.6 Summary and Conclusions

6.6.1 Summary

1. One forming example was studied: (1) Deep Drawing of Honda die using Aluminum 5182-O, 1.2mm
2. FE model was developed and compared with previous experiments to evaluate the accuracy of forming limit diagram to be used
3. FE simulations were conducted to obtain optimum constant blank holder force with and without spacers and variable blank holder force to be used in simulations.
4. Experiments were conducted with and without spacers using constant and variable blank holder force using different blank geometries.
5. Simulation results were compared with experimental results based on maximum thinning
6. The target blank holder force (input to press) given to press was compared with actual blank holder force obtained from press (output from press)

6.6.2 Conclusions

- For the Honda part geometry using Dry + IRMCO lube all samples were formed till 120mm draw depth.
- Better part quality (less wrinkles) can be achieved by deep drawing without spacers and constant blank holder force than deep drawing with spacers.
- Improved blank shape/size can be obtained by using PAMSTAMP
- Ram motion type can significantly affect the cushion response specifically when the die starts to touch the material. To provide the best cushion response the die
should touch the material as slow as possible and then the speed should be increased to maintain the required cycle time

- Preliminary experiments were conducted with dry lube (samples applied with dry lube were stored more than a year). As expected, all samples cracked

- Using Dry + IRMCO lube, experiments were not conducted with servo characteristics (Attach-Detach & pulsating BHF) as all samples were formed using constant BHF (with and without spacers) and variable BHF
References


