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``Single Point Incremental Forming and Multi-Stage Incremental Forming on Aluminium Alloy 1050´´

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ABSTRACT

New innovative and feasible sheet metal forming techniques that can provide good quality product with less manufacturing time, less set up cost and more flexible to any part complexity are very demanded nowadays. Therefore, incremental sheet forming (ISF) is a new technology to takes part in solving many problems from conventional sheet forming process in terms of more flexibility, inexpensive, short production time, suitable for small batches and especially rapid prototype production. The process is easily done on CNC machining centers with a rotating forming tool which moves along predefined trajectories that corresponds to the contour of the desired geometry.

This project aims to provide an understanding of the incremental forming process, specially focusing on experimental SPIF and Multi-Stage ISF tests with the aluminium alloy 1050. The influence of the toolpath and forming tool movement, to obtain a vertical walls, on thickness distribution is studied. For formability investigation, grid strain analysis and measurement will also be determined aiming to study the formability of AA1050 material.

Regarding this work, the target to achieve a vertical wall angle and equally maintain wall thickness along the profile is pursued. Mechanical tests, computer programming, geometry design and mechanical laboratory were required.

Keywords: ISF, forming tool trajectories, toolpath, multi-stage incremental forming, AA1050

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ABBREVIATIONS & SYMBOLS

ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AA	Aluminium Alloy
CAD	Computer Assisted Design
CAM	Computer Assisted Manufacturing
CGA	Circle Grid Analysis
CNC	Computer Numerical Control
DD	Downward Downward Movement
DDDU	Downward Downward Downward Upward Movement
DOO	Downward Outward Outward Movement
DU	Down Up Movement
FEM	Finite Element Method
FFL	Fracture Forming Limit Line
FFLD	Fracture Forming Limit Diagram
FLC	Forming Limit Curve
FLD	Forming Limit Diagram
FLDF	Forming Limit Diagram at Fracture
GAT	Geometry Accuracy Test
HB	Hardness Brinell Scale
IFWCT	Incremental Forming With Counter Tool
INEGI	Instituto de Engenharia Mecanica e Gestao Industrial

ISF	Incremental Sheet Forming
ISMF	Incremental Sheet Metal Forming
ISO	International Organization for Standardization
MAT	Multiple Angle Test
MISF	Multi-Stage Incremental Sheet Forming
MPDF	Multi-Point Die Forming
MPF	Multi-Point Forming
MPPF	Multi-Point Press Forming
RPM	Revolution Per Minute
SMF	Sheet Metal Forming
SPIF	Single Point Incremental Forming
TPIF	Two Point Incremental Forming
UTS	Ultimate Tensile Stress

SYMBOLS		**UNIT**
Ψ	Drawing Angle or Forming Angle	º
φ	Maximum Forming angle	º
α	Incremental Forming Angle	º
σ	Stress	*MPa*
σ_{UTS}	Ultimate Tensile Stress	*MPa*
σ_Y	Yield Stress	*MPa*
A	Elongation at Brake	*%*
E	Young´s Modulus	*MPa*

t	Sheet Thickness	*mm*
K	Strength Coefficient	*MPa*
n	Strain Hardening Coefficient	
ε	Strain	
π	Pie Value	
f	Final Stage	
i	Initial Stage	

CHAPTER 1 INTRODUCTION

1.1 Background

The most famous and common manufacturing process in many industrial and civil sectors is sheet metal forming which are capable of producing good quality complex part with nowadays technology. However, the demand of the customers could have effects on many conventional forming methods when small production batch with high product quality are required. With economic competitiveness, manufacturing companies must find new solutions that are more flexible to satisfy different market segments.

In most of the manufacturing processes, prototyping is a very important step before beginning real operation in mass production. Prototype allows the improvement and development of the product, changing its design in early steps of product development. Producing prototypes in some manufacturing processes may consume a lot of money and time to tryout, especially if specific dies are required as it is the case of sheet metal components.

As a result, a new technology called Incremental Sheet Metal Forming (ISMF) has been developed. The process can be performed on CNC machining centers using simple forming tools to incrementally deform the sheet until the part is produced. The main point of this process is to reduce the lead-time of tooling development and investment cost. ISMF has an ability to form difficult complex parts economically, not requiring specific dies and expensive tool set up. Furthermore, ISMF can be performed in a wide range of materials such as steels, polymers, thermoplastics, titanium, etc. Although the process requires higher manufacturing times when compared to conventional forming process, it is suitable for producing complex parts in small batches, such as prototype parts for aeronautical, automotive and medical applications.

1.2 Objectives

The main objective for this project is to study and experiment the influence of different toolpath on wall thickness distribution of Aluminium alloys 1050 in obtaining vertical wall using multi-stage incremental forming strategies. However, to be able to reach the main target of the project; many experiment and study of single point incremental forming and multi-stage incremental forming must be done as the first stage.

1.3 Scope of Study

The work done within this thesis can be divided in two main areas: firstly, it has been performed the mechanical testing (tensile and hydraulic bulge tests) of the AA1050 to study the material characteristics and to use the obtained information to plot the fracture forming limit line (FFL). Secondly, it was conducted experiments based on general single point incremental forming experimental design on the same material using simple shapes, conical and pyramidal, aiming the study of the process as well as to analyze the single point incremental forming result in the desired parts. Several results are presented: part accuracy, thickness distribution and surface roughness. Regarding the results from this section, it is very useful to predict the behavior of material and to define the plan for the subsequent experimental setup, aiming to obtain vertical walls with multi-stage techniques. An important objective was to perform multi-stage incremental forming using outward strategies. This method was considered aiming to redistribute wall thickness along the shape profile, trying to use the material from the bottom of the part. Finally, a multistage approach was used to study the influence of different tool path on wall thickness distribution. In these experiments, strain measurement was executed in each step to observe the material behavior evolution at each stage of incremental forming by plotting the experimental plastic strains against the fracture forming line.

1.4 Project Plan

Work Plan/Gantt Chart							
Activities/Months	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**Mar.**
Literature review	↔	↔					
Factory Visit	↔						
First experiment on Incremental Forming		↔					
SPIF Experimental Planning			↔	↔			
Experiment on SPIF and part inspection			↔	↔			
SPIF Discussion					↔		
MISF Experimental Planning				↔	↔		
MISF experiment and part Inspection					↔	↔	
Experimental Conclusion and Writing thesis							↔

1.5 Benefits

This project directly benefits INEGI by introducing new strategies in forming sheet metal and/or other sheet material without using mould or die in producing desired parts. This project is the first attempt of experimenting incremental forming on aluminium alloys 1050 which plays an important role for INEGI in experimenting on other material as well as improve the quality of final part. Moreover, this project allows continuing researching and developing incremental sheet forming for medical implant and automobile application in the future.

1.6 Organization of the dissertation

This thesis is divided into 5 chapters, starting with chapter 1 that giving a general introduction, background and objective of the work.

Chapter 2 starts with the literature review of the incremental forming processes, its applications and a more detailed review of the single point incremental forming and the multi-stage strategies.

Chapter 3 gives detail about the experimental work, namely the experimental setup, and its detailed description. At the end of the chapter, the used methodology to inspect the parts is shown.

Chapter 4 provides the final results from each experiment with detailed explanation as well as sets out some relationship between the results.

Finally, chapter 5 presents the conclusion of the work and points out directions for future work.

CHAPTER 2 LITERATURE REVIEW

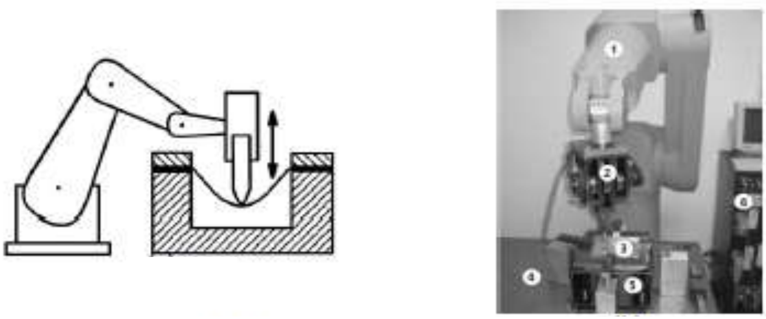
History of sheet forming and sheet forming process those bring an approach to an incremental forming to present incremental forming. Single Point Incremental Forming background and its step and procedure will be explained in the chapter as well as two point and multi-stage incremental forming. At the end of the chapter, an important of each parameter that effects on incremental forming and present of different forming tool path will be described.

2.1 Sheet Metal Forming Process approaching Incremental Forming

This part present overview of sheet incremental forming, there are many process of sheet metal forming that has an incremental approach technologies such as Hammering, Spinning, Multi-Point Forming, Stamping, Laser Forming Process and Water jet Process.

2.1.1 Hammering

Hammering is considered as the one of the oldest Incremental Sheet Forming process, it is traditionally a manual process. However with technologies involved it could be processed with CNC machine and nowadays using robot arm technology nowadays to help and control tools movement. In particular, robot arm will punch clamped sheet with small step in each cycle as circular trajectory to forming into shape [Fig.2.1].



(a) (b)

Figure 2.1: Incremental Hammering Process
(a): Incremental Hammering Process Scheme [14]
(b): Industrial Robot [28, 29]

2.1.2 Spinning

Spinning forming process is one of a metal forming process by which sheet metal is rotated at high speed and formed into axially symmetric part. Process could be performed on CNC machine or by hand, when spinning a localized force is applied to a workpiece causing over flow the block. There are two types of spinning forming process, Conventional Spinning and Shear Spinning.

Conventional Spinning [Fig.2.2a] is steadily formed by using roller or rounded tool. Tool pushed against the blank until roller conforms to the contour mandrel. Final part is definitely having smaller diameter than initial blank but has constant thickness. This process is suitable for small series of production due to many sequences of steps hence low tool production cost in this process is a great choice.

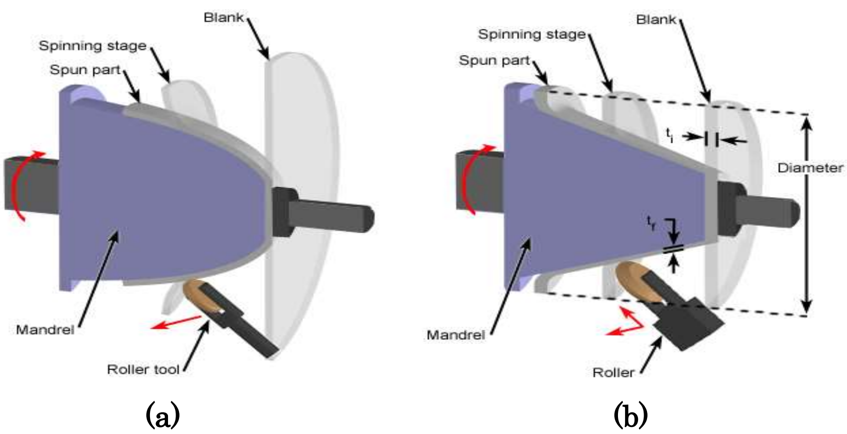


Figure 2.2: Spinning Forming Process
(a): Conventional Spinning [8]
(b): Shear Spinning [3, 8]

In Shear spinning [Fig 2.2b], roller will have two actions of bending sheet against mandrel and also applying downward force while rotating. Regarding to that action causing outer diameter of final part equal to initial part but wall thickness will not be constant. Thickness variation in shear spinning follows well known Sine law (Eq.2.1) [Fig.2.3].

$$t_f = t_i \sin\alpha \qquad \textbf{(2.1)}$$

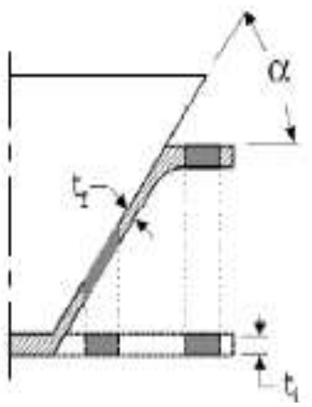


Figure 2.3: Deformation of sheet metal in shear spinning [21]

2.1.3 Multi-Point Forming (MPF)

Multi-point forming [Figure 2.4], multi-point die forming (MPDF) or multi-point press forming (MPPF) technology is a flexible 3D manufacturing process for varied large sheet which similar to forming process of solid dies. In Solid die, two opposite solid die (upper and lower) are used to press onto a blank and form into particular shapes. Instead, MPF used matrix punches with specific shape that could adjust height by mean of line actuator [23]. Due to the rapid change of two element group, several special MPF techniques that are impossible in conventional forming have been investigated. For instance, spring-back is compensated cycle by cycle, large deformation could be obtained and large size of sheet can be formed in small scale MPF equipment.

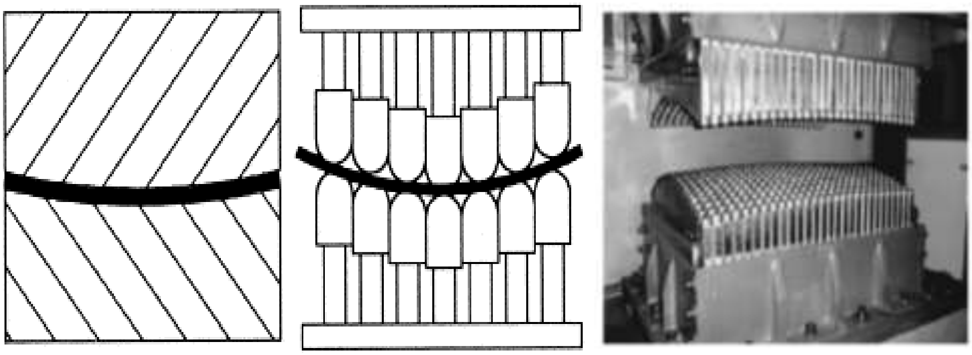


Figure 2.4: Multi-Point Sheet Forming [17]

2.1.4 Stamping

Stamping or Pressing process [Fig.2.5], it is single stage operation where each stroke of press produces final desired parts or could be with various stages. Stamping process associated with many operations such as punching, bending, flanging, stretching, drawing and coining. Stamping press and stamping die are the main tools used to produce high volume sheet metal parts. Parts achieve their shape through an effect of die tooling.

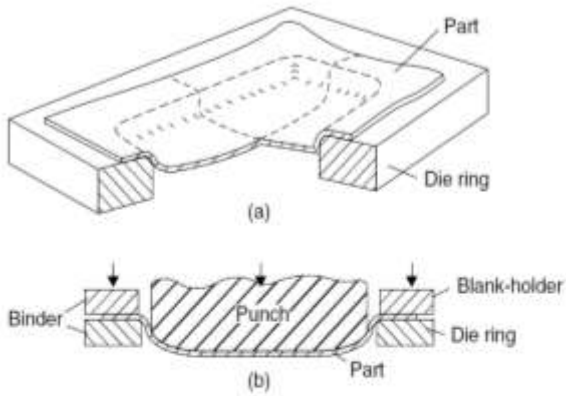


Figure 2.5: Typical part forming in stamping process

2.1.5 Laser Forming Process

Laser forming [Fig.2.6] is a non-contact method, providing shaping of metallic and nonmetallic components. It is form by introducing thermal stresses into the surface of workpiece area by irradiation laser beam which thermal stress induce plastic strain bending the material and result in local elastic plastic buckling. However laser forming process proposed some disadvantages such as high energy consumption, high forming stand cost, need of personal safety and pre-coating of sheet surface to increase an absorption coupling [5].

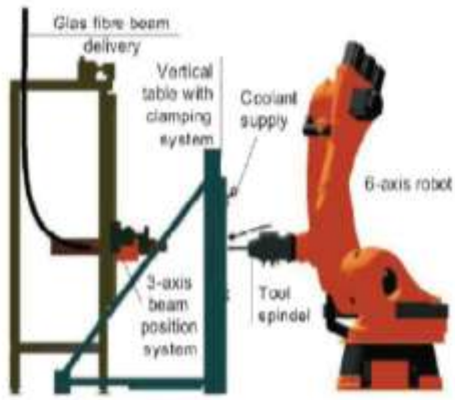


Figure 2.6: Laser Forming Process [5]

2.1.6 Water Jet Forming

Water Jet Forming [Fig.2.7] is one of sheet forming process that no rigid tool required. It was developed specially for a small batch of manufacturing of nonsymmetrical shape of shallows shell. This method can erasure the tool marks and form without lubricant oil. To use water jet forming method, membrane theory and momentum theory of hydrodynamics must be considered [16]. Water jet forming has an advantage of more flexibility, less tools requirement, low cost of equipment and better surface due to no tool contact [5].

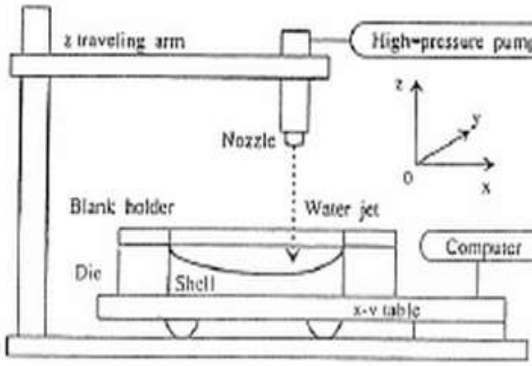


Figure 2.7: Water Jet Forming Schematic diagram [16]

2.2 Incremental Sheet Forming Process

Incremental sheet metal forming process using single point tool was created by Leszak in 1967 [30] which later on well known as Dieless Forming. Later in 1994 Matsubara [22] had developed an Incremental Backward Bulge Process, where sheet is clamped on downward moveable rig, at the center of blank is supported by a post as shown in [Fig.2.8]. Forming tool is control by CNC providing rotating tool movement that describes trajectories to obtain final desired part in either symmetrical or non-symmetrical geometry.

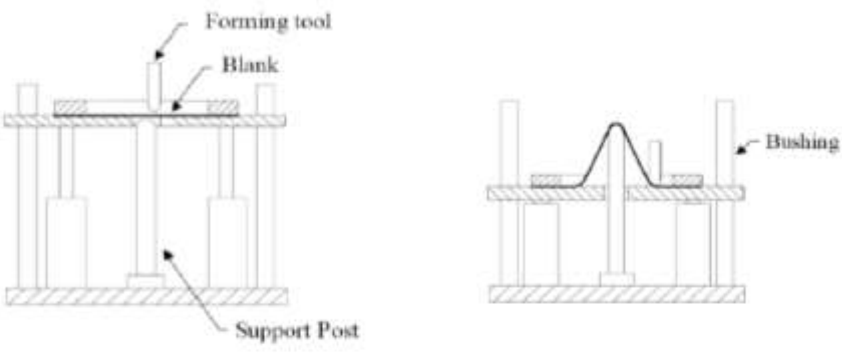


Figure 2.8: Incremental Backward Bulge Process [21]

Concept of incremental forming process has been developed to use on CNC milling machine by Jeswist [31] and Leach et al. [32] and no backing plates was used. Moreover, Kitazawa [33] had later on improved an Incremental Stretch Expanding process [Fig.2.9], where CNC lathe machine is used with steel rod hemispherical forming tool tip. Blank is clamped with the chuck on lathe machine, according to blank and tool rotation relationship effect this process to have limited to symmetric geometry.

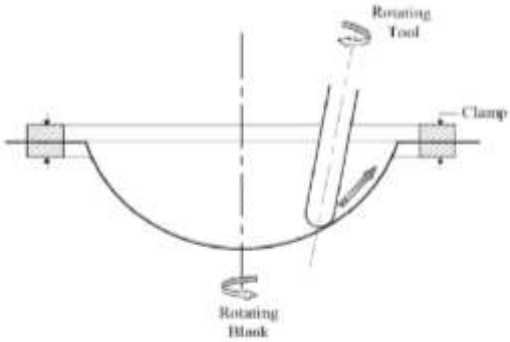


Figure 2.9: Incremental Stretch Expanding Process [22]

Strong Point of Incremental forming is the simple process which consumes shorter steps to produce parts. The process will first start with the design in CAD Program and then transfer to CNC Machine and select suitable backing plate and clamping jig. After processing only some finishing are required hence the process is as simple as shown in [Fig.2.10] and [Fig.2.11].

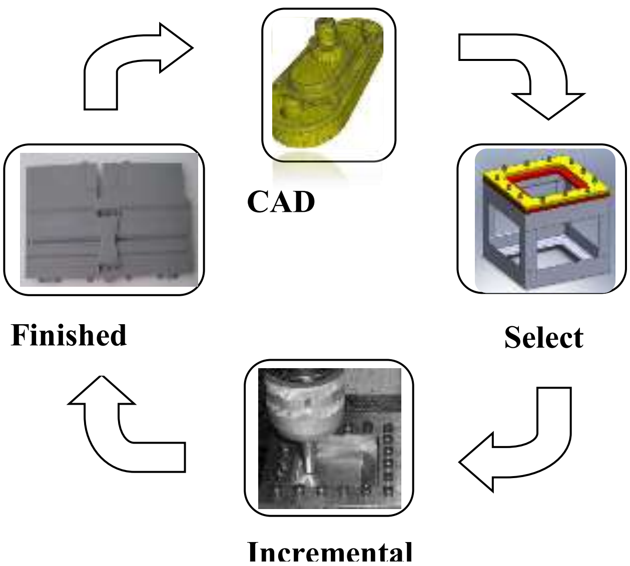


Figure 2.10: Steps of Incremental Sheet Forming (ISF)

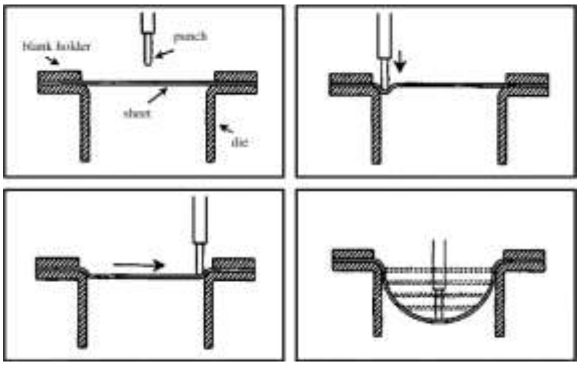


Figure 2.11: Simple Steps of Incremental Sheet Forming

The product of this process can be made directly from 3D CAD model to finished product without any dedicated die or tools. Therefore, the ISF process offers the rapid prototyping advantage of short leads time, high flexibility and lower cost for small batch applications.

The process of incremental forming [Fig.2.11] starts with clamping a sheet with the rig and set the forming tool into position. Once the machine starts, the forming tool spins and move follow the trajectories in order to obtain the desired part. Then the part can be used without any additional process. The work piece can typically be used for molding, prototype or components. Most of the ISF application are medical products, aeronautical application and automotive as a prototype. The Incremental Sheet Forming mainly divided into three different types [25], Single Point Incremental Forming (SPIF), Incremental Forming with Counter Tool and Two Point Incremental Forming (TPIF) which will be explained later in the following sections [see Fig.2.12].

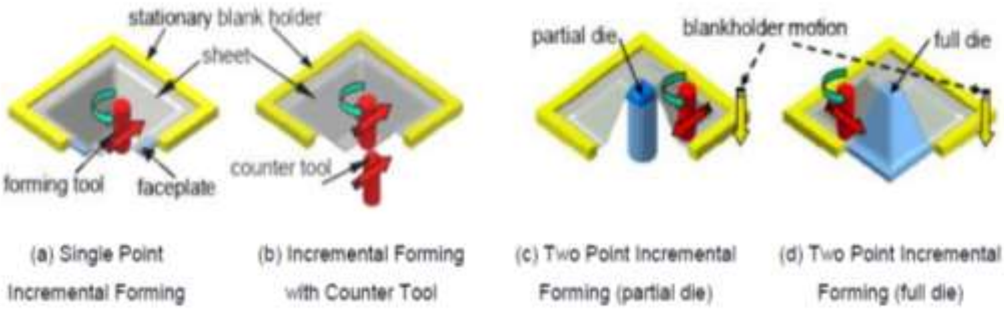


Figure 2.12: Different Configuration of three types of ISF [20]

2.2.1 Introduction to SPIF

Single Point Incremental Forming (SPIF) process is done by clamping blank sheet in stationary clamping system and let the forming tool describes the contour of expected geometry which will be controlled by CNC machine as shown in [Fig.2.13]. SPIF is a process that proposed a new contribute to incremental forming like spinning and stretch expanding which is a process for producing non-axisymmetric parts [18].

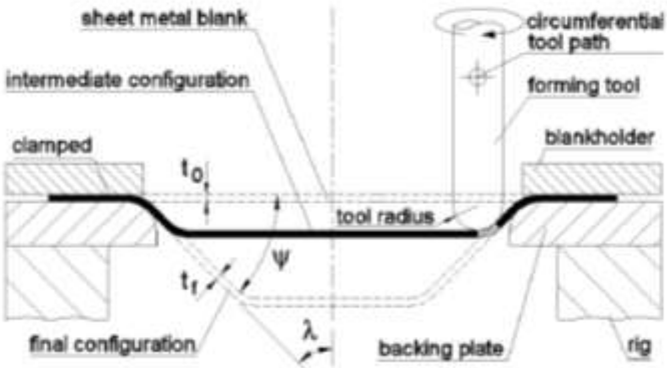


Figure 2.13: Schematic of cross section view of SPIF Process [12]

Fig.2.13 shows the component of SPIF which has backing plate, blank holder, forming tool and some important parameters explained later in the next chapter. In this picture no die support is used.

Regarding Single Point Incremental Forming there is some advantages as shown below [34]:

- Small force due to incremental nature of process;
- Conventional CNC machine can be used to perform ISF;
- Final desired part produce directly form CAD file;
- No positive or negative die requested;
- Increasing material formability;
- Parts dimension can only be limited by machine tools;
- Good surface finish quality;

On the other hand there are some disadvantages included below [20]:

- SPIF takes longer forming time that conventional deep drawing process;
- SPIF have less geometry accuracy especially at bending edges area and convex radius. Comparing to other Incremental sheet metal process [35];
- Process is restricted by small size production batches;
- To achieve vertical angle, it can only be by multi-stage strategies;
- Springback occurs even though it can be minimized by some correction algorithms;

2.2.2 Important Parameters for SPIF

In SPIF, each parameter mentioned below; sheet material, tool size dimension, forming angle, step size, feed rate, spindle rate, sheet thickness and lubricant; have their own influence on the process in different ways such as part accuracy, formability, maximum forming angle, thickness distribution etc. Hence it is important to notice what parameter has the most effect on the result in order to obtain perfect desired parts.

Sheet Material

Sheet material and its own properties has an influence on formability regarding to study of Frantini et al. [36]. According to the study, they had found that strength and strain hardening coefficient (n) had the most influence on formability compare with other properties such as strength coefficient (K), ultimate tensile strength (σ_{UTS}), elongation at break (A) and normal anisotropy index (R_n) as show in Table 2.1. Strain hardening coefficient shows most different between different materials on formability [37].

Table 2.1: Influence of material properties parameter on Conventional Forming and Incremental Forming

	Influence	
Properties parameters	**Conventional Stamping**	**Incremental Forming**
n	No	High
K	High	Moderate
$\boldsymbol{\sigma_{UTS}}$	No	No
A	No	Moderate
$\mathbf{R_n}$	High	Low

Tool Size

Tool Size greatly affects surface finish and formability of a part; it has defined that smaller tools radius influence more formability than larger radius tools [38]. The matter of fact is larger tool radius has more contact area with sheet during the process and also increasing more forces to the surface. In contrast, smaller tools diameter; concentrated zone of deformation appears more as well as less contact surface resulting in higher strain low stress then more formability [37]. Nevertheless, the stability and stiffness of tools does not allow too small diameter [39].

Forming Angle

Forming angle (Ψ) is the angle between the side of wall and XY horizontal plane [see Fig.2.13]. Forming angle mainly rely on material properties and sheet initial thickness [37]. SPIF part is limited by Maximum forming angle in single incremental forming. However, Martinis el al. [40] tried to predict the maximum forming angle concerning the material properties and forming parameters as in (Eg.2.2).

$$\Psi = \frac{\pi}{2} - e^{\varepsilon t} \qquad \textbf{(2.2)}$$

Where t is thickness at fracture of limit formability therefor εt is thickness strain which calculated from plane strain and equi-biaxial stretch test in FFL. The equation represents the onset of fracture due to combination of FFL in principle strain space and maximum forming angle at onset of fracture.

Step Size

Step size or Step down or tool pitch define how much material had deformed per revolution. This parameter is still debatable parameters. Some thesis proves the step size does have an influence only on surface roughness not formability. Besides other trust that by increasing step size it decrease formability. However, Ham et al.[41] has clearly showed that step size does not have a significant effect on formability in his study. Moreover, smaller step size seems to take longer time in manufacturing parts.

Forming Speed

Feed rate (mm/min) and Spindle rate (rpm) are an important parameter concerned for this forming method. The heat generated by friction is directly proportional to relative motion between tools and material sheet. Generally, it is believed that formability could be increase with speed due to heat effects but other negative side effect might arise too [37]. Increasing the speed could leads to rough surface finish and waviness on surface [42]. Besides, forming with high rotational speed increase the likelihood of improve tool marks on sheet surface [25].

However, this problem has been confirmed that the speed of the forming tool has an influence on formability. Faster tool feed rate decreasing formability causes by lower heat generated in tool interface and also resulting in lower localize heating [43].

Moreover, Both Ham and Jeswiet [43] and Ambrogio et al. [44] claim that spindle rate has an influence on formability by increasing spindle rate, formability increase as well. Due to the fact that local heating on sheet and reduction of friction between tool and sheet but too much tool spindle could damage tool wear.

Sheet Thickness

In general, wall thickness would follow sine law prediction [45, 46] (see Eg.1) but wall thinning might not be uniform as sine law [45, 47]. From the study of Hussain et al [47] showed that thickness result did not follow sine law in conical shape at the area of inner edge of backing plate and near fracture area [20].

Though, Ham and Jeswiet [43] had concluded that increasing thickness resulting in increasing formability due to more material to be drawn.

Lubrication

Lubricant however is important to single point incremental forming in term of reducing tool wear and decreasing heat generated from friction. Regarding Bramley [48] work, he claimed that lubricant type is not a major factor but necessary for obtaining good surface finish. Other, Kim and Park [49] concluded their work on testing the influence of lubricant (with and without) on both ball tip tool and hemispherical tool.

In conclusion, formability increased with ball tool without lubricant but if too much friction occurs, leads to faster fracture. Later, new conclusion of Carrino et al [50] claimed that high friction different only happened in extreme condition (with and without) lubricant.

Part Geometry

Complexity of part geometry has large effects on manufacturing time and forming force. To form difficult angle for example right wall angle, multi-stage is required which consume more time. Many methods must be used to obtain good surface finish and good wall thickness distribution. The most common shapes analyzed are the truncated cone [51, 52] and truncated pyramid [52], [53].

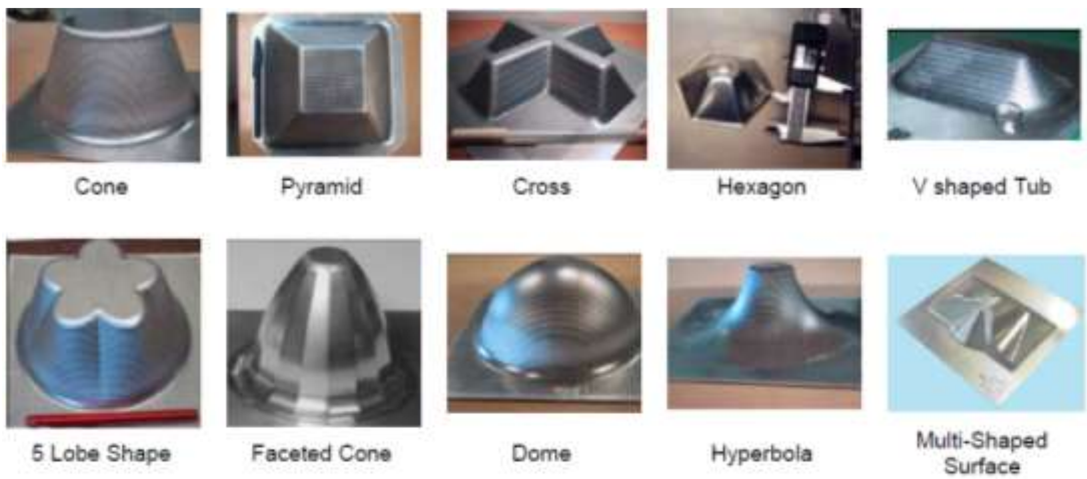


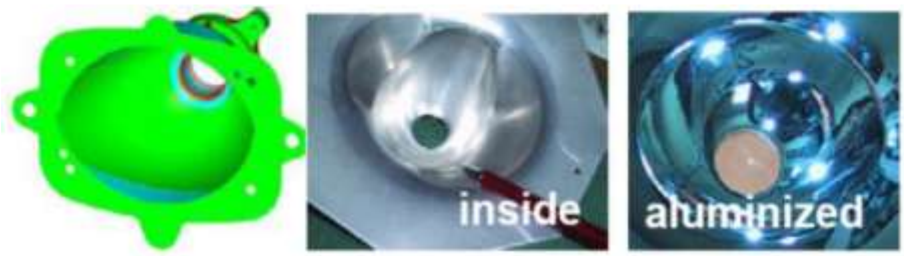
Figure 2.14: Other complex geometry by incremental sheet forming [25]

Other complex geometry is also studied as in [25]. Each shapes given different strain but sine law is applicable only in conical shape. Ham and Jeswiet [54] design experimental on dome, cone and pyramid, result showed that pyramid has maximum forming angle and dome shape vice versus. Even though the average effective strain in conical is the higher than pyramid and dome shape [20].

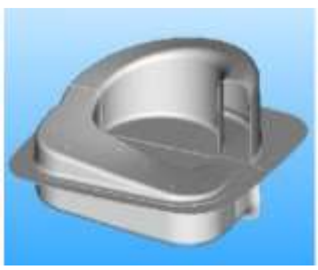
2.2.3 Incremental Sheet Metal Forming Application

Mostly incremental sheet metal forming application can split into two categories: rapid prototypes for automotive industry and non-automotive industry. In the field of automobile, heat or vibration shield [Fig. 2.15], reflective surface of headlights [Fig. 2.16a], solar oven [Fig. 2.16b] and Silencer housing for trucks [Fig. 2.16c] are manufactured by Incremental sheet forming.

Figure 2.15: Heat or vibration shield for automobile [9]



(a) Reflective surface of head light [9]



(b).Solar Oven [13] **(c).Silencer housing [26]**

Figure 2.16: Reflective surface of automobile headlight [2],[9]

Nontheless, there are some application that involved with medical application as seen in Fig. 2.17; by an attepmt of Ambrogio et al. [27] who had made an angle support, further Duflou et al. [55] had made Cranial plate for implant surgery using Incremental Sheet Forming to manufacturing parts [20].

Figure 2.17: Cranial plate for medical application [27]

2.3 Incremental Forming with Counter Tool

This process or the other hand is called Kinematic Incremental Forming, it is a techniques that required no backing plate but there will be counter tool which moves the same trajectories as main forming tool which they support each other instead. An auxiliary tool is considered as a kinematic support instead of static support. The study of the process is complete by Jadhav [6] [see Fig. 2.18].

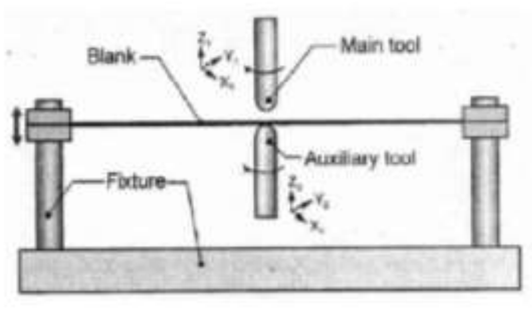


Figure 2.18: Schematic of Incremental Forming on Counter tool [6]

2.4 Two Point Incremental Forming

In Two Point Incremental Forming or TPIF process blank holder can be moved in Z axis however forming tool works the same way as in single point incremental forming but with die support. Two point incremental forming is separated into two categories which are with partial die or with full die as subscribed below.

2.4.1 Partial Die Two Point Incremental Forming

Regarding this process, sheet is clamped without able to move up and down due to supported post under some essential area of the blank. Tool moves as incremental forming movement follow support tool which stay fixed below sheet, however part is formed from the inner area of blank to the outer side. There is no wrinkling in this process due to local shear occurs rather than stretching and the rest of sheet will maintain its original dimension regarding to Jeswiet [56]. Although this process requires static support but it helps enhancing geometry accuracy and support post can be adapted to use with other geometry [19] [see Fig. 2.19].

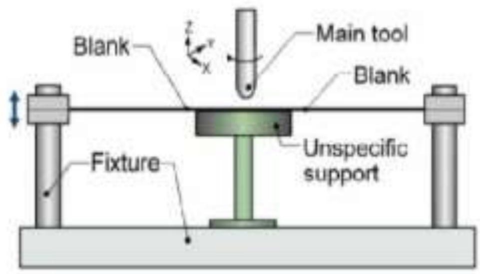


Figure 2.19: Schematic of Two Point Incremental Forming (Partial Die) [19]

2.4.2 Full Die Two Point Incremental Forming

For two points incremental forming [see Fig. 2.20] with full die, it is not considered as dieless approach since full die is fixed to support the sheet while forming tool just describe around full die. It is similar to conventional spinning but giving more part accuracy.

Through using full die, manufacturing time tends to increase as well as production cost although it increases more geometry accuracy [35]. It is important to notice that the support is specific for geometry only, thus new support shape is needed for new geometry [57]. As well as it must be associated with sheet material since poor flexibility must be concerned.

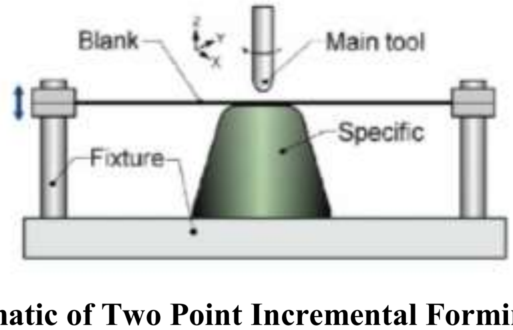


Figure 2.20: Schematic of Two Point Incremental Forming (Full Die) [19]

2.5 Multi-Stage Incremental Forming

Regarding to Sine law (Eq.2.1), it is hard to obtain bigger angle while having the same thickness throughout the part. It is complicated to have big and deep drawing part without fracture because the more the forming angle the less the thickness distribution. Right wall angle or vertical wall leads wall thickness to reach zero regarding sine law. Increasing the maximum wall angle could be enchanced by many ways such as increasing sheet thickness, changing tool diameter and step down also have an influence on maximum forming angle [58].

Therefore multi-stage is another strategy to obtain large wall angle by redistribute material or shift the material with multi-stages. Hirt [58] who had attempt to perform incremental forming which tool moves several times over same area through the geometry profile to increase wall angle with partial support [see Fig. 2.21], hence this process become related to multi-stage incremental forming [57].

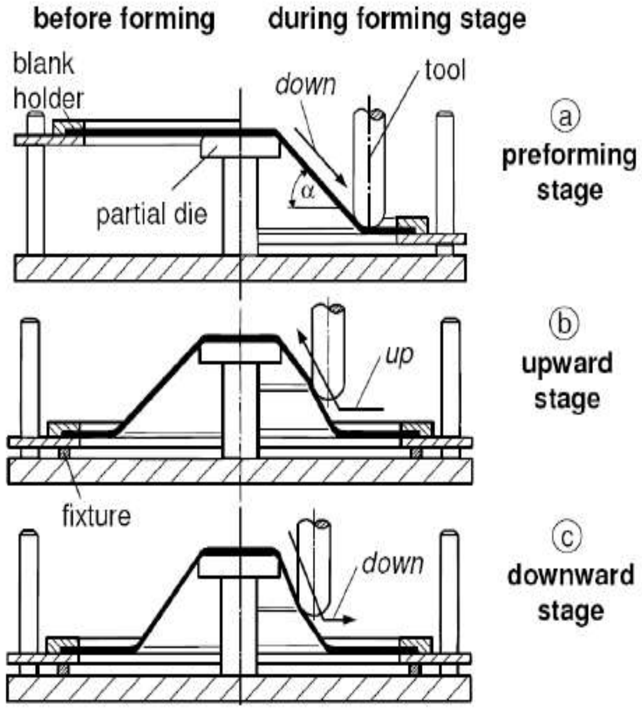


Figure 2.21: Single Point Incremental Multi-stage strategies [58]

In fact, the first multi-stage idea was improved by Kitazawa [59] on axisymmetric parts [20]. It is later proposed by Skjoedt et al. [26] to make vertical wall using multi-stage single point incremental forming on a cone without any support as shown in Fig. 2.22.

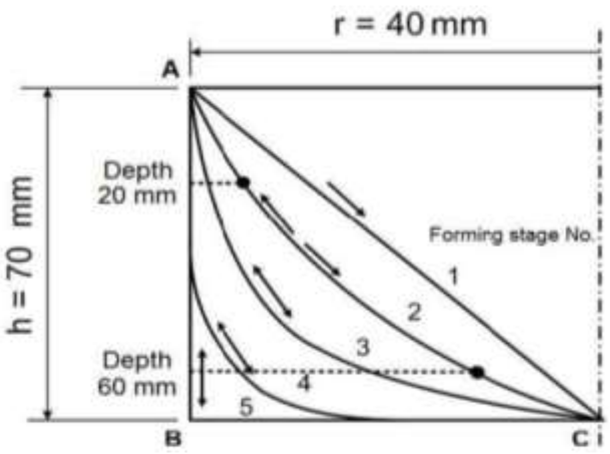
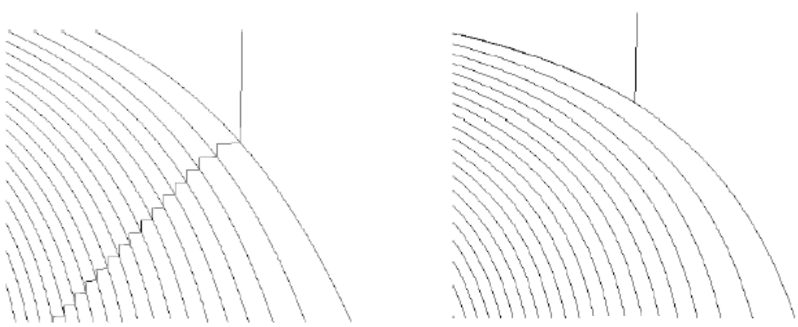


Figure 2.22: Five Stages multi-stage incremental sheet forming [60]

2.6 Tool path and Different movement

It is important to obtain good accuracy and surface quality by concerning toolpath. Mostly, toolpath selected must have constant step depth for each layer [25][Fig. 2.23a]. During manufacturing toolpath would create marks in transition point between each layers and influence poor surface on flat surface when high steps are used [20].



(a) (b)

Figure 2.23: Incremental Sheet Forming Toolpath [20]
(a).Constant Step Depth
(b).Spiral Toolpath

However, to improve this problem spiral or helical toolpath [Fig. 2.23b] or either scallop height can be used [3, 29][Fig. 2.24].

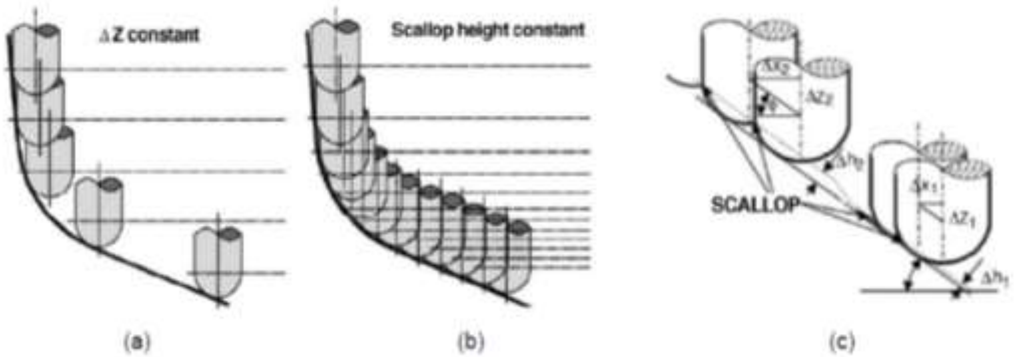


Figure 2.24: Incremental Sheet Forming Toolpath [20]
(a).Constant Step Depth
(b).Constant Scallop Height
(c).Definition of Scallop Height

2.6.1 Downward Movement and Upward Movement

This kind of movement mostly used in multi-stage incremental forming. At the first stage downward movement is absolutely the first movement and follow by either upward or maintain downward again over same trajectories as first stage to distribute strain and wall thickness. The amount of stages of upward and downward depends on complexity of shape and material used. Both movements are also used as a part of obtaining right wall (vertical wall). Regarding Joao Luis [23] study, his work shows that DU (down up) strategies give less thickness at deeper depth comparing to DD (down down). [see Fig. 2.25].

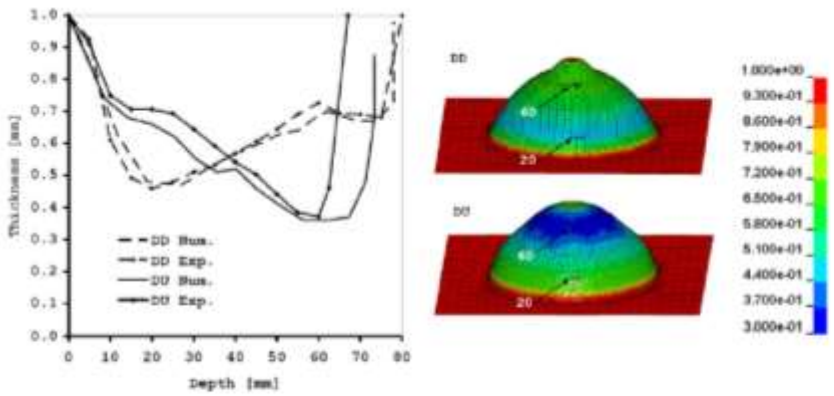


Figure 2.25: Thickness Distribution between DD and DU Movement [18]

2.6.2 Outward Movement

According to Hald et al.[10], he presented another multi-stage movement called Outward movement in order to obtain vertical wall. Outward in this case is done at constant Z coordinate by pushing material from the bottom outward to used formed on the wall side. Hence the main idea is to thinning bottom area [see Fig. 2.26].

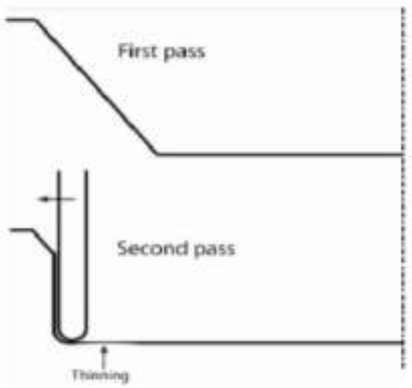


Figure 2.26: Outward Movement [10]

2.7 Forming Fracture Line (FFL)

It is important to predict the forming limit diagram at fracture (FLDF) or forming fracture line (FFL) especially in forming case where forming is controlled by fracture instead of necking like incremental forming. However FFL curve could be plot by performing hydraulic bulge test to determine a biaxial stress and tensile test to determine uniaxial tension of material. To achieve FFL experimentally, grid pattern must be printed on the sheet and when sheet is deformed it becomes ellipses then major and minor strain could be investigated. Then Forming fracture line of both rolling and transverse direction was plotted according to an experiment as mentioned.

Regarding this fracture line, it will limit the capability of sheet form in the case of process that limited by fracture. This means that if FFL is well away from material strain or lies in proper region, it could increase the probability of material failure.

The observation of morphology of cracks and the measurement of thickness along cross sectional part of SPIF shows that plastic deformation occurs by uniform thinning until fracture without evidence of localized necking take place before fracture [20, 61]. Referring to previous research [23, 57], it claimed that the FLCs of conventional sheet metal forming are inapplicable for predicting SPIF failure. Instead FFL present fracture strain placed well above FLC must be used in SPIF [23] as seen in Fig. 2.27.

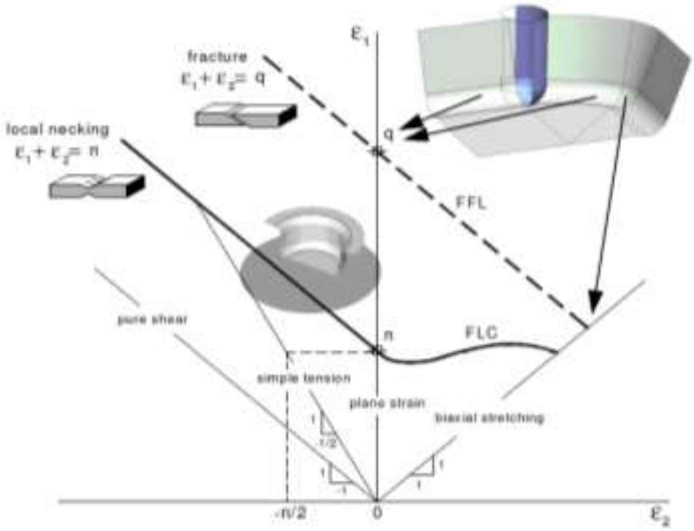


Figure 2.27: Schematic of Forming Limit of SPIF against stamping and deep drawing [20]

CHAPTER 3 EXPERIMENTAL WORK

In the first part of this chapter, material characterization will be defined and utilized by creating Fracture Forming Line (FFL) using several mechanical tests which will be explained in detail. It is important to define the FFL before planning on experiment because FFL can predict the behavior of material during incremental forming as well as predicting fracture. Then next part will explain about an experimental set up that involves in this work as well as all apparatus used in the experiment. Single point incremental forming part inspection using many techniques to obtain data will also be included at the end of the chapter.

3.1 Material Characterization

FLC or Forming Limit Curve is normally chosen to evaluate the limit of strain concentration and proportional straining before necking. However, FLC only describe necking limit for conventional sheet forming process but does not define the failure or fracture for incremental forming. Therefore, FFL or Fracture Forming Line is necessary for Incremental process. Many parameters such as yield stress, tensile stress, thickness strain, young´s modulus, ultimate tensile stress and other important parameters will be determined through tensile and bulge test to predict material characteristics and material´s forming capability.

3.1.1 Tensile test

Tensile test is one of the most common ways to obtain material strength and material characteristic placing defined specimen under stretching force. This test allows finding stress-strain curve as well as a point in the negative side or uniaxial tensile of FFL curve [Fig. 2.27] while the other side will be investigated by bulge test. After reaching the uniform strain, local necking occurs on the specimen.

In this case six specimens are subjected to a uniaxial stress in order to determine material properties of Al1050-H111. Tensile test is performed on INSTRON 4500 Tensile Testing Machine [Fig. 3.1] following the standard ISO 6892-1:2009 (E). Machine parameter was set to sample rate of 2 pts/sec and crosshead speed of 5 mm/min. The program used for data acquisition is Instron Series IX, available at INEGI mechanical test laboratory.

Figure 3.1: INSTRON 4500 Tensile Test Machine

Tensile specimen is machine with the specific dimensions [Fig. 3.2] according to normative and a mark with circular grid is printed as shown in Fig. 3.3. Specimen has flat geometry of 1 mm thickness with rectangular cross sectional.

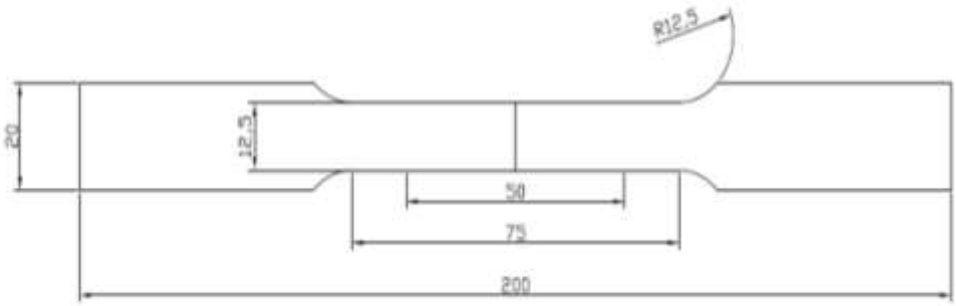


Figure 3.2. Tensile test specimen dimension [11]

Some parameters such as crack width, crack angle and crack thickness from cracked part will be investigated for FFL curve plotting. To measure crack width, Vernier caliper and an Optical Microscope were used for crack measurement. Crack angle was measured with Solidwork program as shown in Fig. 3.4.

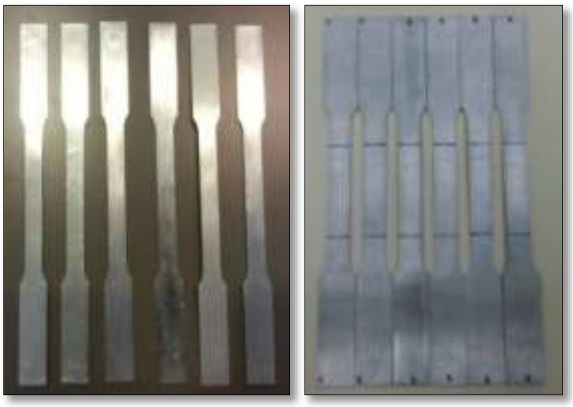


Figure 3.3: Tensile Test Specimens

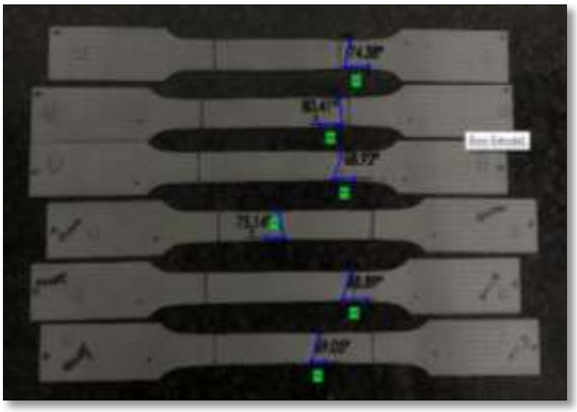
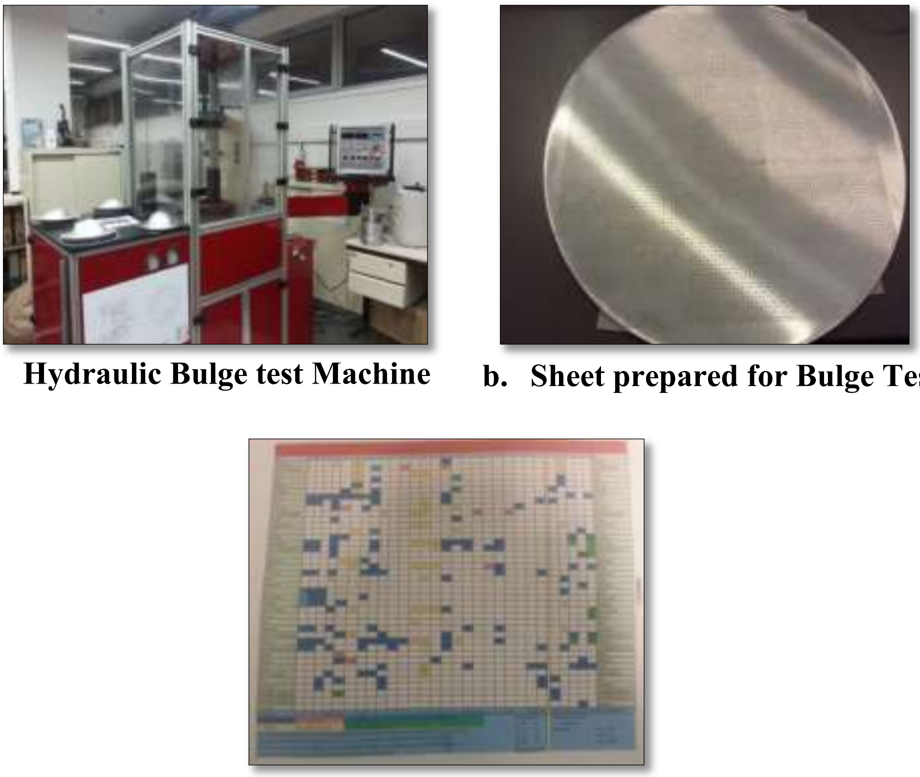


Figure 3.4: Crack angle measurement

3.1.2 Hydraulic Bulge Test

Apart from tensile test, bi-axial circular hydraulic bulge test is performed in INEGI Hydraulic Bulge Test Machine [Fig. 3.7a]. The objective is to achieve points on the right side of FFL curve, at a biaxial stress stage. Due to the biaxial state of stress, material failure by local necking and cracks follow later. Bulge test allows to find yield stress up to higher forming degrees when compared to conventional tensile test [62].

Sheet will be clamp tightly in hydraulic bulge machine and then subjected under biaxial expansion using very high oil pressure until sheet cracks. There are six specimens involves in the test. Firstly, sheet is cut into 250 mm diameter circular sheet and marked with 4.847 mm circular gird by electrochemical etching [Fig. 3.7b].



a. Hydraulic Bulge test Machine **b. Sheet prepared for Bulge Test**

c. Electrochemical Etching

Figure 3.5: Hydraulic Bulge Test Apparatus

Electrolyte and Neutralyzer are selected from Electrochemical etching table [Fig. 3.7c] provided by INEGI which shows possible electrolyte and neutralyzer for each material. In this case, electrolyte ME15 and neutralyzer N1 are selected using output voltage of 4 volts. Oxidation produced better grid printed than electrochemical etching comparing the same level of output voltage.

Investigating final hydraulic bulge test part [Fig. 3.8], many parameters must be obtained, for example crack thickness, crack width and stretched circle dimension to compare with initial circular grid. In order to measure crack thickness, bugle test part must be cut and measured using the microscope. It is challenge to measure stretched circular grid dimension due to non-flat surface and, therefore, tape or flexible rulers could be applied to achieve correct distance.

To achieve data for FFL curve, gauge length and fracture width will be measured after the sheet cracks which appears in transverse direction for all specimens. Initial thickness and original strain before fracture will be compared with final value and, by using Eq. 3.5, it allows to determine major and minor plastic strain for FFL curve.

Figure 3.6: Final part of Hydraulic Bulge Test

3.1.3 Fracture Forming Limit Line

Concerning the construction of fracture forming limit line, gauge length or thickness at fracture [Fig 3.7] and width of the sample before and after fracture occurs [Fig. 3.8] must be determined. Measuring gauge length is very time consuming and the process must be done precisely on the microscope. Average value of several measures seems to shows the best result.

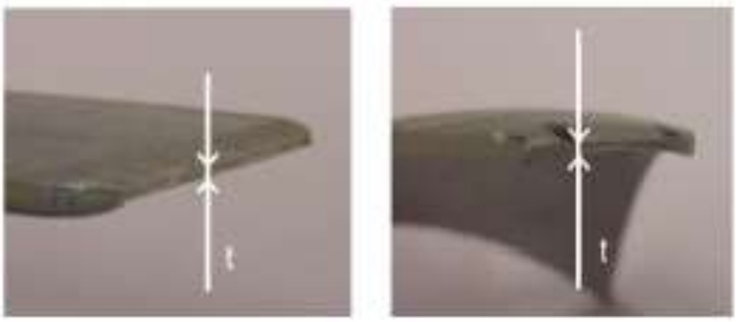
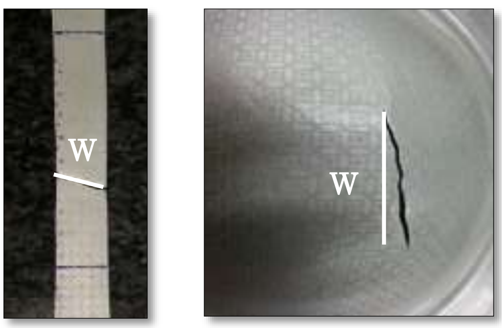


Figure 3.7: Gauge length area of measuring [5]



(a) **(b)**

Figure 3.8: Width of sample at fracture
(a). Fracture width in tensile test
(b).Fracture width in bulge test

An experimental fracture forming line could be plotted by applying parameter to the incompressibility equation, ε_3 representing Thickness strain, ε_2 and ε_1 standing for the in-plain strain (see Eq.3.1). Tensile test data will be plotted on the left side of the graph and incline down to bulge test data on the right side of the graph.

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \qquad \textbf{(3.1)}$$

Plain strains will be obtained from knowing thickness and the in-plain minor strain, minor strain could be found using (Eq.3.2) and the thickness strain by using (Eq.3.3).

$$\varepsilon_2 = \ln(\frac{w}{w_0}) \qquad \textbf{(3.2)}$$

$$\varepsilon_3 = \ln(\frac{t}{t_0}) \qquad \textbf{(3.3)}$$

3.2 Plan of Experiment

Firstly, single point incremental forming is performed for general investigating reasons. Two general geometries are formed: Conical and Pyramid, the process allows an understanding of using CNC machine and incremental forming procedure from the beginning. This experimental set up [Table 3.1] allows us to find the maximum forming angle in both shapes with single point incremental forming and to study many relationships between parameters.

Secondly, outward strategy [Table 3.2] is tested in order to study the influence of outward movement in making vertical wall and redistributing the wall thickness along the profile. On the same hand, we are capable to observe material behavior during outward movement with multistage incremental forming. Experiment is divided into three stages: first stage corresponds to conventional incremental forming and continues with outward movement on the second and third stage, being this one performed with constant step over. The outward operation is done on a moveable clamping device as shown in [Fig. 3.33]. All the experiment could be concluded as shown in Fig. 3.9.

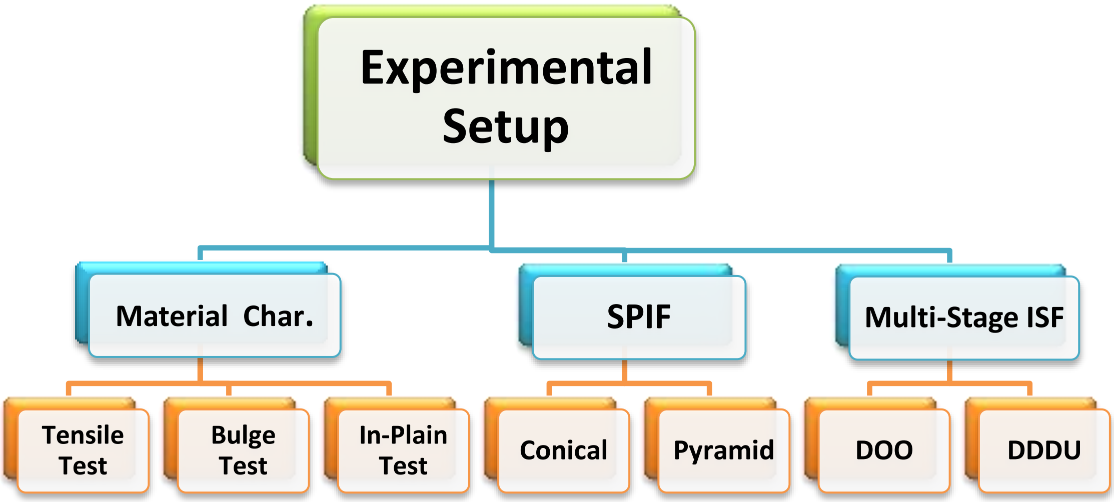


Figure 3.9: Hierarchy Chart of all experimental

As the material characterization was already discussed in the previous part of this chapter, therefore more detail about incremental forming will be show in separated table for each experimental set showing essential fix parameter and general dimension. Table 3.1 shows the parameter for single point incremental forming of both conical and pyramid geometries.

Table 3.1: General Experimental Parameters for Single Point Incremental Forming

Geometry/Parameters	Conical	Pyramid
Initial sheet thickness (mm)	1	1
Tool	Hemispherical, Φ12 mm	Hemispherical, Φ12mm
Feed Rate (mm/min)	1000	1000
Clamping system	Circular backing plate on non-removable jig holder	Rectangular backing plate on non-removable jig holder
Lubricant	Total finarol B5746	Total finarol B5746
Initial Wall Angle (º)	30º	30º
Forming tool	Hemispherical 12 Dia.	Hemispherical 12 Dia.
Step side (mm)	0.18	0.18
Part Depth (mm)	75	75

For multi-stage incremental forming, there are two main experimental sets using multi-stage strategies in order to obtain vertical wall which are DOO (or Downward, Outward and Outward movement) as shown in Table 3.2 and DDDU (or Downward, Downward, Downward and Upward Movement) as shown in Table 3.3.

In the first part Outward movement was examined in order to notice any helpful in wall thickness distribution of this movement before planning for the next experiment of making vertical wall.

Table 3.2: Outward Movement (DOO) with Multi-Stage Incremental Forming

Steps/ Parameters	Stage 1	Stage 2	Stage 3
Movement	Downward	Outward	Outward
Wall angle (º)	45	90	90
Depth (mm)	15	15	16
Step Down (mm)	0.18	-	-
Step Over (mm)	-	0.25	0.25

Finally, concerning multi-stage strategy, incremental forming of each step will help increasing forming angle [18] and drawing more material to be formed. Hence, an experimental setup [Fig. 3.10] is set to examine the influence of downward, upward movement and outward movement with multi-stage incremental forming on wall thickness distribution, to observe the strain distribution along the profile of geometry in each stage and to try to obtain vertical wall. It is also to revise Camara [23] work and try to obtain similar result. Revising his work allows us to understand more about multi-stage incremental forming and clearly see how downward, upward and outward really affects material distribution. Therefore process [See Fig. 3.11] is mainly divided into four stages with different angle and depth but suing same trajectories in each stage. In this part only conical geometry will be formed and analyzed. Apart from general incremental forming test in [Table 3.1] this multi-stage incremental forming is done on moveable clamping jig in [Fig. 3.33].

To remark, in all experiments some parameters are fixed as constant conditions which are feed rate (1000 mm/mim), spindle rate (0 rpm), forming tool shape and size (Hemispherical shape with 12 diameters), lubricant (TOTAL FINAROL B5746) and CNC machine (3 axis OKUMA MC-40VA).

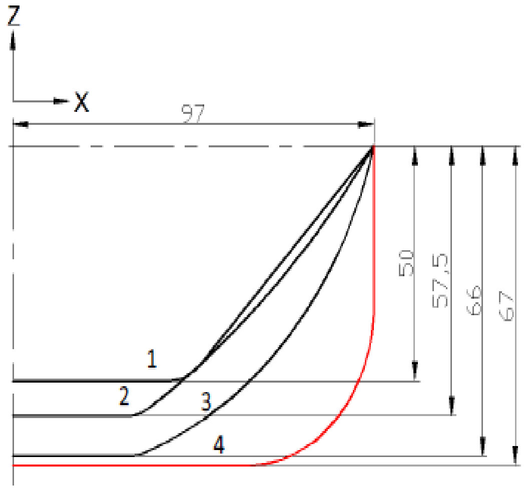


Figure 3.10: Schematic of multi-stage toolpath to obtaining vertical wall on conical shape [23]

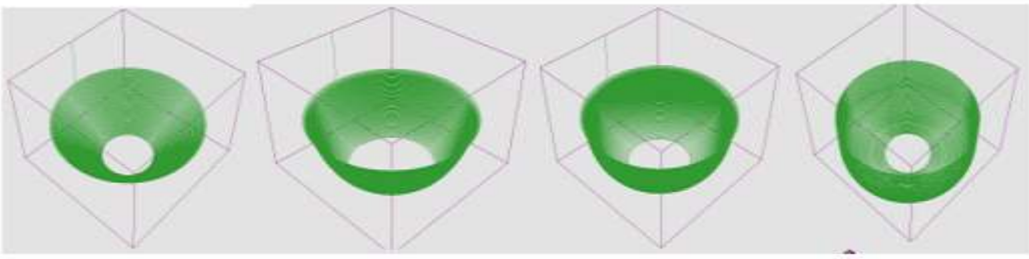


Figure 3.11: CAM toolpath of multi-stage for obtaining vertical wall of conical geometry [23]

Table 3.3: Multi-stage incremental forming for obtaining vertical wall (DDDU)

	Stage 1	Stage 2	Stage 3	Stage 4
Movement	Downward	Downward	Downward	Outward & Upward
Angle	45 °	Curvature R225.5 mm	Curvature R95.5 mm	Curvature R34 mm
Depth (mm)	50	58	65	67

3.3 Experimental Setup

Experimental set up part will describe an important apparatus used in this experimental operation which include description of sheet metal, forming tool, CNC machine, backing plate, clamping system and lubricants

3.3.1 Sheet Material

The material selected is 1 mm thickness of Aluminium Alloy A1050 with H111 temper designation. The initial sheet has a size of 250 x 250 mm as shown in Fig. 3.12. After cutting, sheet metal must be kept safe avoiding having any defect on the surface due the fact that this aluminium alloy is easily deformed. Therefore, roughness test and thickness inspection value will be very close to real value.

Aluminium Alloy 1050 has a composite of many elements according to Table 3.4, but the most outstanding element is 99.5 % Aluminum. This means that this alloy is almost pure aluminium.

Figure 3.12: 250 x 250 Aluminium 1050-H111 sheet for SIF manufacturing

Table 3.4: Aluminium Alloy 1050 elements composition

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti	Etc.
Weight %	99.5	0.25	0.4	0.05	0.05	0.05	0.07	0.05	0.03

Material characteristic of Al and Al1050 will be compared in terms of physical and mechanical properties as shown in Table 3.5 and Table 3.6.

Table 3.5: Physical Properties Composition of Al and Al 1050-H111

Material Property	Al	Al 1050-H111
Density (g. cm^{-3})	2.70	2.71
Melting Point (ºC)	660.32	650
Thermal Expansion (µm/m.K)	23.1	23.1
Thermal Conductivity (W/m.K)	237	230
Electrical Resistivity (Ω.m)	28.2×10^{-9}	282×10^{-9}
Modulus of Elasticity (GPa)	69	69

Table 3.6: Mechanical Properties Composition of Al and Al 1050-H111

Material Properties	Al	Al 1050-H111
Tensile Strength (MPa)	70	80
Yield Strength (MPa)	20	120
Ultimate Tensile Stress (MPa)	50	10
Young´s Modulus (GPa)	70	70
Shear Modulus (GPa)	26	26
Elongation on 50 mm (%)	25	35

Before manufacturing process began, square blank of sheet metal must mark before by using Electrochemical Marking method to print the grid [Fig. 3.23]. For Aluminium 1050, Electrochemical Oxide Method with the voltage up to 4 voltages is most preferable process due to clearly grid printed on Al 1050. Electrolytes are ME 15 with Neutralizer N1 according to Sheet metal electrochemical manual shown in Fig. 3.15c. Grid printed on the sheet covers most of the area of the sheet as seen in Fig. 3.13 with grid size of 4.847 mm diameter. A detailed view of the grid appears in Fig. 3.14.

Figure 3.13: Sheet metal with grid marks

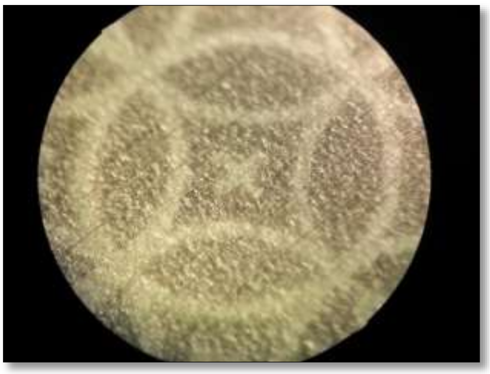


Figure 3.14: Grid Geometry through microscope

To measure the dimension of the grid using a microscope with 200x lens is required [Fig. 3.15]. Moreover, sheet must be hold still in order to avoid errors.

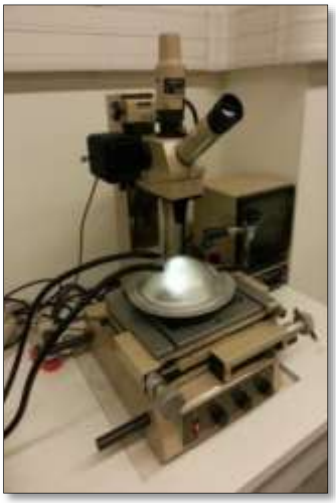


Figure 3.15: Microscope used to measure grid dimension

3.3.2 Forming Tool

Forming tools used are a hemispherical shape with 12 mm diameter tip and a ball tip also with 12 diameters. Hemispherical tool is used for performing single point incremental forming and outward forming, while the ball tip tool is used for multi-stage incremental forming of vertical walls. In hemispherical tool, vertical part of the tool has 16 mm above the tip. Both tools are made from PM300 tool steel (ISBN 0-8493-9013-3) with normal hardening heat treatment in order to increase hardness and wear resistance level. The tools are presented in Fig. 3.16 and Fig. 3.17.

Both tools were made by the Mechanical Engineering machining shop at University of Porto. In this case only one forming tool is used to perform all of the manufacturing operation. Tool has properties according to Table 3.7.

Figure 3.16: Hemispherical forming tool with 12 diameters tip [1]

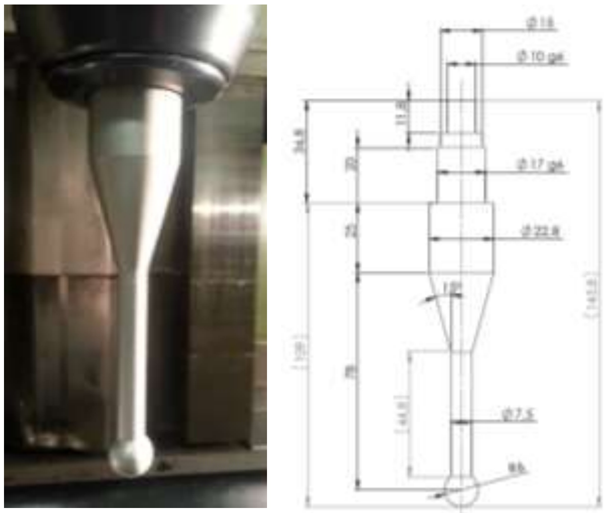


Figure 3.17: Ball tip forming tool with 12 diameters tip

Table 3.7: Forming tool properties

Properties	Value
Density	7.85 g/cc
Hardness	310 HB
Specific Heat Capacity @ 100ºC	28 W/m-k
Thermal Conductivity	12.8 µm/m-®C
Major Component Element	94.52 % Fe

The most important quality of forming tool are having good hardness and good wear resistance in order to give good surface finish and accuracy final part. Therefore, forming tool in this project must have good treatment to enhance those quality required.

In this manufacturing, free spindle speed of forming tool is helping in neglecting the friction between tools and sheet metal increasing more formability [20]. Moreover, the ball head tool is more effective than using hemispherical head tool in term of formability [49].

3.3.3 CNC Machine

For manufacturing experimental parts, OKUMA MV-40 VA 3 axis vertical CNC machine in Fig. 3.18 was used to perform the operation. It is located at the Department of Mechanical Engineering workshop of the University of Porto.

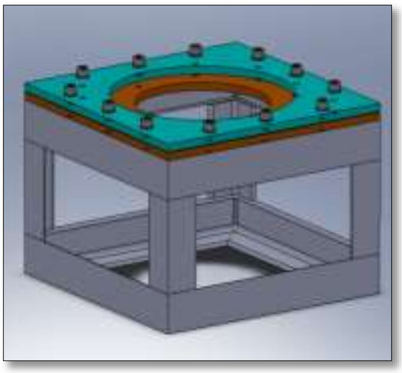
Figure 3.18: OKUMA MC-40VA CNC 3 axis vertical milling machine at Faculty of Mechanical Engineering workshop [13]

Table 3.8: OKUMA MC-40VA 3 axis CNC machine´s specification

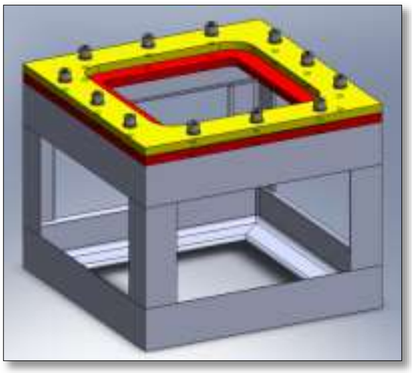
OKUMA MC-40VA Basic features	
Machine type	Vertical
Control	CNC
Number of Axes	3
X Axis Travel (mm)	762
Y Axis Travel (mm)	430
Z Axis Travel (mm)	450
Motor Power (kW)	7.5
Max. Tool Storage Capacity	32 ATC
Machine Speed (mm/min)	1-4000

3.3.4 Backing Plates and Clamping System

To clamp sheet metal, jig must be used to hold sheet metal during the operation. Sheet will be locked in place with twelve screws around the sheet. Each Jig contains different backing plate, either circular or rectangular, depending on final geometry. Backing plates has the function to avoid large deformation of the sheet during forming as well as to help obtaining desirable geometry. This clamping system is provided by INEGI, specially designed for incremental forming on OKUMA CNC machine. [See Fig. 3.19 for sheet holder]



a. Circular backing plate sheet holder [1]



b. Rectangular backing plate sheet holder [1]

Figure 3.19: Backing plates and clamping system

3.3.5 Lubrication

Sheet metal is lubricated by using the lubricant TOTAL FINAROL B5746 [see Fig. 3.20], which is a lubricant used for conventional stamping process. Same lubricant will be applied to every ISF experiment.

Applying lubricant is necessary to smooth tool´s movement, to reduce roughness of final surface, to reduce wear surface of forming tool and to reduce heat generated from friction between forming tool and sheet metal.

Figure 3.20: Lubricant for ISF manufacturing

Lubricant will be applied directly to the surface where the tool moves passed in small amounts at a time. Lubricant must be cleaned and reapplied again when there are many scrap floating in the lubricant in order to prevent bad surface roughness.

3.3.6 Grid Marking

Grid marking is a process of printing a significant line or circular patterns on to the surface of the area of interest of sheet. Grid marking is done in order to measure the strain at specific areas after forming. There are many methods that can be used to print the grid: serigraph, silk-screen printing, electrochemical etching, photochemical etching and laser etching [63]. However, grid printed must not affect any forming process [7]. Each method differs from each other in terms of resolution, pattern´s accuracy, contrast, durability and quality [64]. There are many types of grid used as shown in Fig. 3.21.

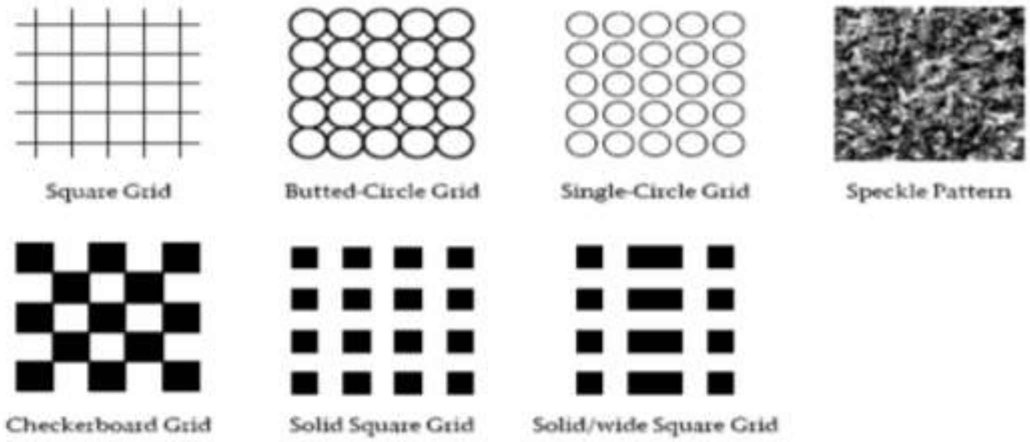
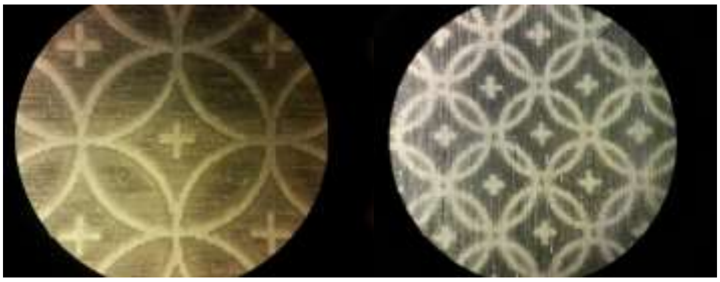


Figure 3.21: Different type of grid pattern [4], [24]

In the experiments, grids in Fig. 3.22a and Fig. 3.22b were chosen to print on Aluminium alloy 1050 sheet surface with electrochemical oxide method. Grid in Fig. 3.22a is used in single point incremental manufacturing and outward experiment but grid in Fig. 3.22b is used in multistage incremental forming. Both pattern used voltage of 4 volts. The most suitable electrolyte M15 and neutralyzer N1 as mentioned before.



(a) ***(b)***

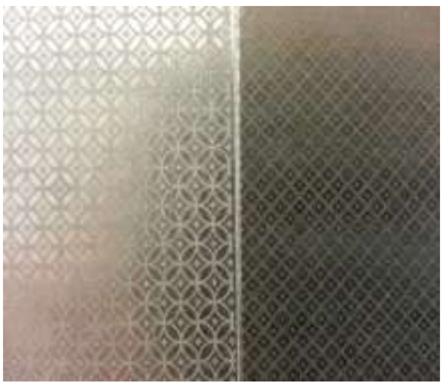


Figure 3.22: Grid marking used for aluminium alloy 1050

Grid marking procedure

In this case, electrochemical marking method is selected. It was first used by R.H. Heyer [15] and it is one of the most famous methods used for grid printing on sheet metal forming. This is because of its easiness of application, cost effectiveness [65], does not cause any distortion and is durable during forming [66].

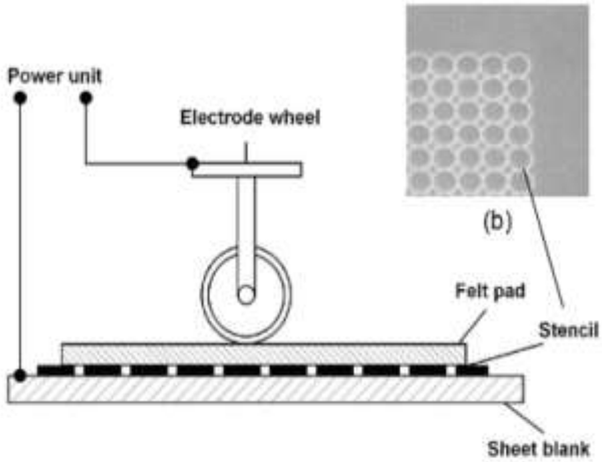


Figure 3.23: Schematic of Electrochemical Etching [7]

The basic principle of this method is shown in Fig. 3.23. It requires a low voltage power supply, a stencil, a felt pad and an etching solution as an apparatus. The steps to achieve the grid can be described as follows:

1). Connect power source with electrode and sheet. Carefully placed stencil grid pattern on the blank; sheet surface must be cleaned before stencil is placed.

2). Wet the felt pad with etching solution and placed onto the surface; avoid wrinkling during placing process. Each etching solution is dependent on material type as shown in Fig. 3.15c and it is really necessary to choose right solution suitable to material.

3). Roll an electrode roller wheel that attached with power source on the felt pad constantly and try to roll cover all stencil patterns.

As a result of voltage placed across electrode wheel and blank surface, grid pattern from stencil is etched on the sheet surface automatically [24]. After etching, sheet should be washed with neutralizing solution in order to wash out the etching solution away. This method has many advantages when compared to other grid marking method shown in Fig. 2.24.

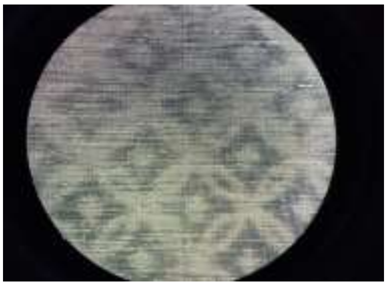
Grid marking method	Parameters								
	Accuracy	Quality, resolution and contrast	Durability	Resistance to friction/lubricants	Resistance to temperature	Applicability of different material	Cost effectiveness	Required time	Applicability of large parts
Electro chemical etching	A	B	A	A	A	D	C	A	C
Screen printing	B	A	A	B	C	A	A	A	C
Photochemical etching	B	B	C	B	C	A	D	D	D
Laser etching	A	A	A	A	A	C	D	D	A

A = Excellent, B = Good, C = Average, D = Poor

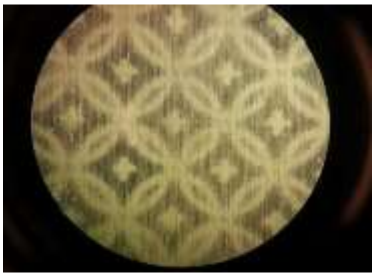
Figure 3.24: Comparison of the grid marking methods [24]

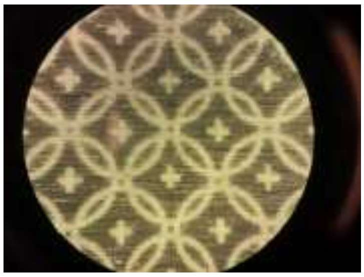
Grid printing on aluminium, one has selected grid pattern in Fig.3.22b for multi-stage incremental forming. To select voltage supply, different voltage supply must be tested with the same grid pattern in order to obtain the best grid accuracy, contrast in order to clearly see through microscope [see Fig. 3.21].

Four different voltages were tried from 0.5 up to 2 volts. Grid marks of each voltage applied shows completely different result as shown in Fig. 3.25. After looking through microscope, the result of grid marking using 2 volts has given the best grid marks compares to all four types. Therefore Grid with 2 voltage supply is chosen to print the grid on the sheet for manufacturing.



0.5 volts   1 volts





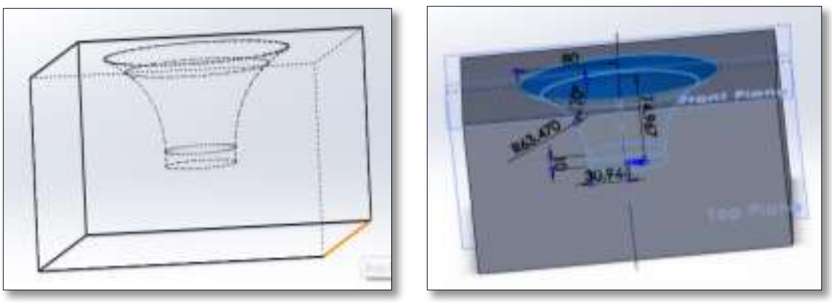
1.5 volts   2 volts

Figure 3.25: Grid with different voltage supply

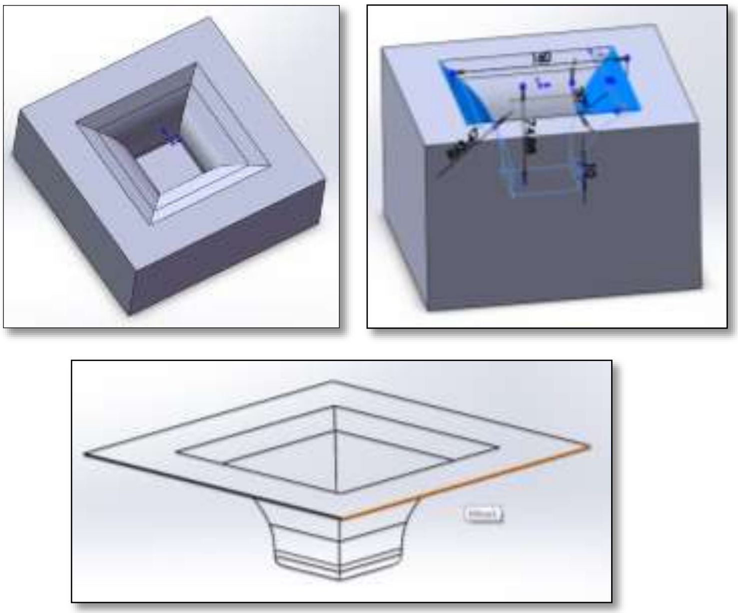
3.4 Programming Procedure for ISF Experimental

3.4.1 Solidwork geometry design

There are two general geometries: conical and pyramid. Both geometries are created in Solidwork program [see Fig. 3.26] and have the same starting forming angle of 30º and followed by integrated forming angle until reaching 90 º angles at the bottom of shape. The reason of angle variation is for detecting the maximum forming angle of each type of material for the first time.



a. Conical Geometry and its dimensions



b. Pyramid Geometry and its dimensions

Figure 3.26: Solidwork geometry design

The conical has maximum depth of 74.968 mm, with the top radius of 80 mm and bottom radius of 30.94 mm. Conical geometry has a curve of 63.47 mm radius as same as a side wall of pyramid geometry. Pyramid has maximum depth of 74.55 mm. and 10 mm. depth of vertical wall at the bottom end. Upper square of pyramid is 160 mm. width and 62.39 mm width for bottom square.

Since Mastercam X6 program don't have incremental forming feature, to be able to perform a tool path on CAD/CAM program, part needs to be in shape of rectangular cubic not a sheet metal shape. Instead of cutting or milling, we use the same tool path but with different kind of tool to perform incremental forming. Solidwork part needs to be saved in IGES file type to be used with Mastercam X6.

3.4.2 CAD/CAM program

CNC program codes for each shape are made from Mastercam X6 program. IGES file of Solidwork´s geometry will be uploaded to Mastercam X6 and setting the tool path. The condition of the operation is shown in Table 3.9.

Table 3.9: Specification condition of creating Mastercam code

Parameters (unit)	Feed rate (mm/min)	Spindle rate	Retract rate	Step down (mm)	Plunge rate	Spiral limit
Value	1000	0	1000	0.18	1000	0.2

To perform a code of conical and pyramid geometry, contour surface finishing mill toolpath must be selected, except for outward movement toolpath that requires area clearance of surface high speed toolpath. All parameters in Table 3.9 are common for both conical and pyramid shape but surface area selected could be different. The tool is set to move spirally downward with 0.18 mm step down. In this case, spindle rate is set to be zero because tool will not be rotating due to specific contact area with sheet. Only the tip of the tools that touches the sheet during first forming step. However, tool will automatically rotate more at some specific area depending on the geometry, for example, more than 45 degree angle wall.

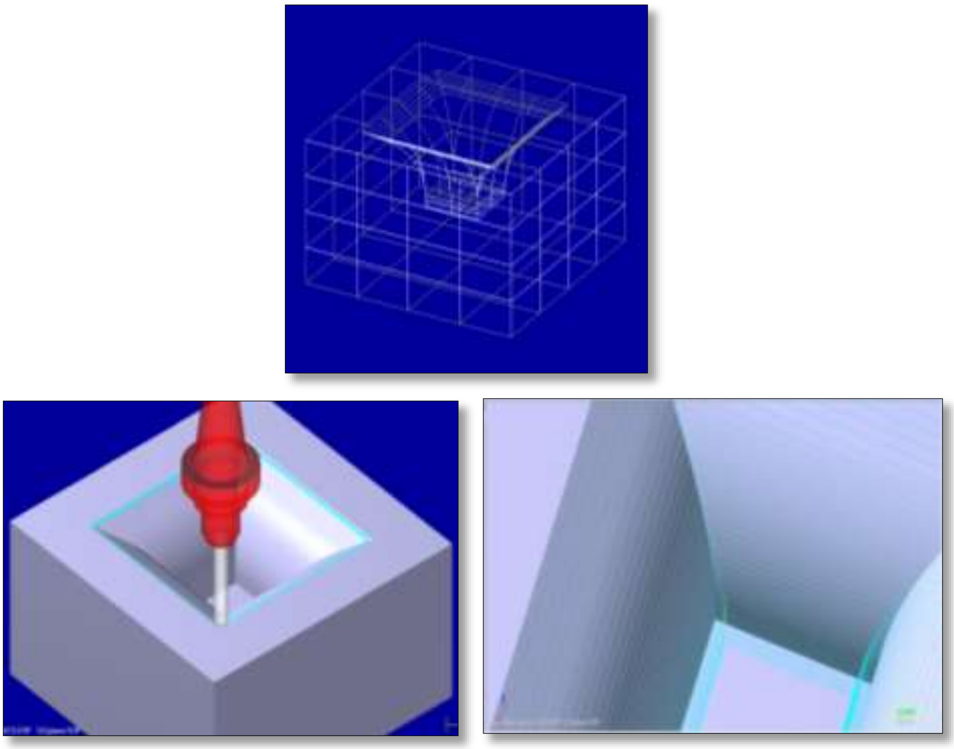


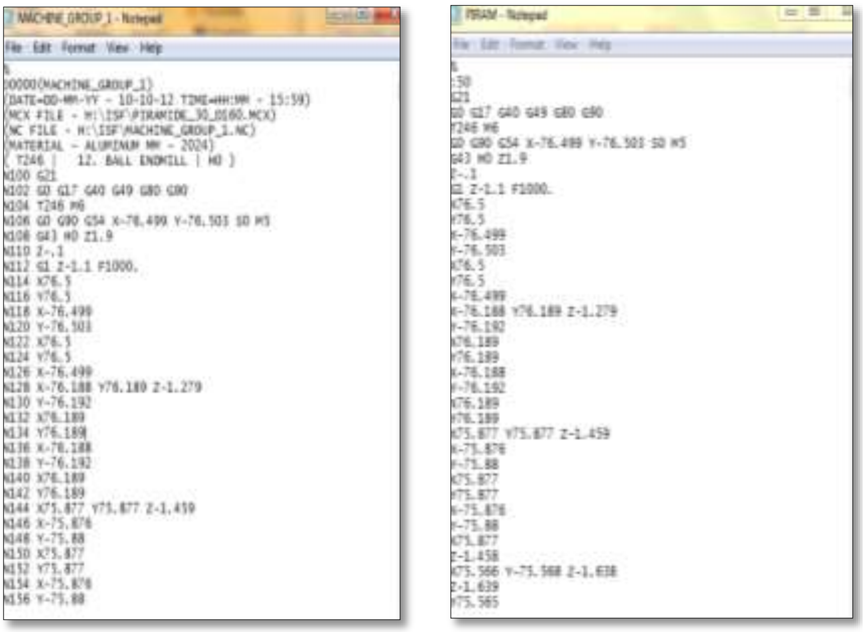
Figure 3.27: ISF Tool path in Mastercam X6 Program

Tool path [Fig. 3.27] will be created after all parameters are set and surface area has selected. Program code will be provided after tool path simulation has been performed and saved as text file. The resulting NC file can be opened on Notepad program for code correction.

3.4.3 Numerical code eliminated program

After final code has produced, numerical code part that lies in front of the code in every line must be eliminated because numerical term will not be red by CNC machine during the manufacturing. Renum program [Fig. 3.28] is required to take this responsibility in erasing numerical part and final code [Fig.3.29] should be saved as PRO file type in order to be used in of code splitting later with next program.

Figure 3.28: Renum program used for eliminating numerical part



b. Code with numerical part   a. Code without numerical part

Figure 3.29: ISF code for CNC machine

3.4.4 NC Code Splitter program

Finally, the code needs to be split into many small parts depending on how long the code is. The reason for this split is due to the fact that CNC machine from Mechanical Engineering workshop has constrain of short memory. Therefore two codes can be uploaded to machine at a time and previous must be deleted before next upload. The program is called NC Splitter [Fig. 3.30] having as input file a NC files and producing MIN file type after finish code separation.

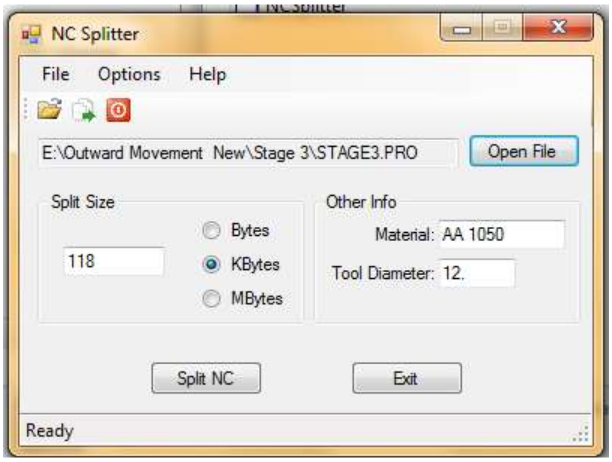


Figure 3.30: NC Splitter program for code splitting

This constrain causes little defect on finish surface from tool stopping after one code is finish. Hence tool tip defect are created on the inside surface of sheet metal due to the intermittent tool movement, and surface roughness value could be affected.

3.5 Incremental Forming Experimental Procedure

3.5.1 Single Point Incremental Forming

3.5.1.1 Conical Geometry

To start the process, all code must be uploaded onto CNC machine and set the forming tool in placed before clamping the sheet. It is important to clamp both tool and sheet tightly before starting. Then set zero of all three axes must be done carefully. Next, used hemispherical tool to form the part by moving along the toolpath as set in CAD program until obtain desired part. In the first line of the code single block or single code running is required before running other line of the code to make sure that the tool runs at the same coordinate as the code. Final part of conical shape is shown in Fig. 3.31.

Figure 3.31: SPIF of Conical Geometry

3.5.1.2 Pyramid Geometry

For pyramid shape, all parameters and equipment used are similar to conical shape as a mean of fix parameters. All the procedure for this shape is also similar to conical shape as well. The reason of making two different shapes is to observe the influence of shape on SPIF. Even though, both shape required different range of code for CNC machine. Final part of Pyramid shape is shown is Fig. 3.32.

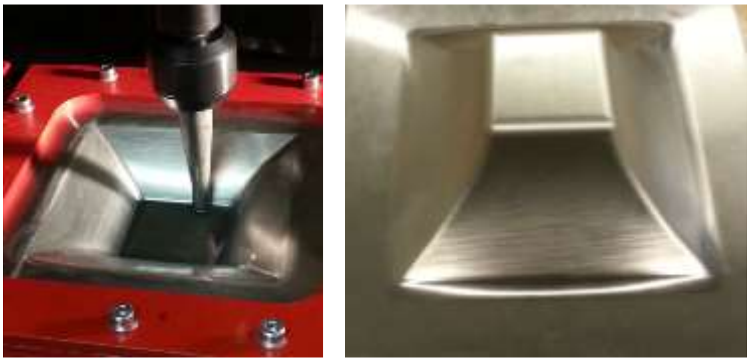


Figure 3.32: SPIF of Pyramid Geometry

3.5.2 Multi-Stage Incremental Forming

3.5.2.1 Outward Movement (DOO)

Outward movement is one movement used in multi-stage incremental forming besides downward and upward movements. It is recognized as a movement for forming vertical wall by redistributing or shifting a material to be used at other area and to make used of material at the bottom of the part. This part of experiment is performed to study the behavior of material under outward movement and to study the influence of outward movement on wall thickness distribution.

Outward operation is done on new jig that is provided by INEGI. This jig allows sheet clamping part to be removed from the jig which benefits the change of incremental method. It permits a die to be used, changing the position of previous formed sheet and allows sheet to be removed and replaced again without losing same coordinate as shown in [Fig. 3.33].

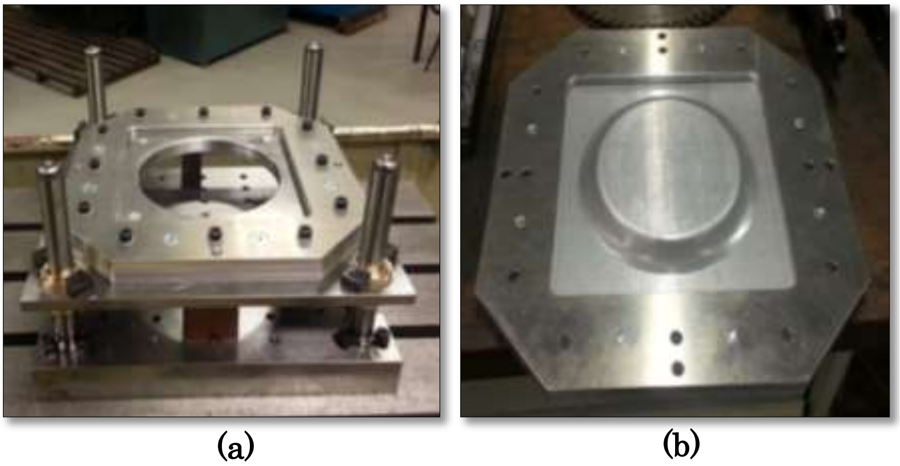


Figure 3.33: Moveable Clamping System
(a): New Jig system for Incremental forming process on CNC Machine
(b): Removable part of new jig or clamping system

Outward movement procedure

As mention in Table 3.1, outward movement is split into three different stages, normal downward, outward and outward with 1mm step down. In the first stage [Fig. 3.34], initial angle starts at 45º angle with 15 mm depth.

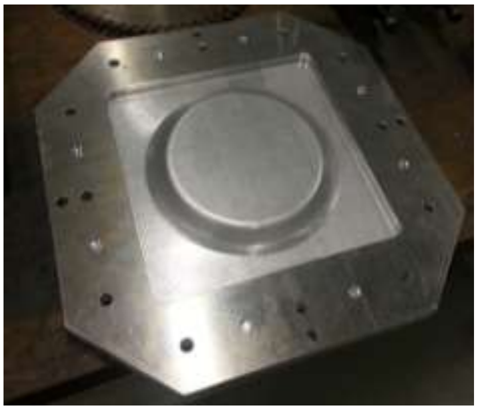


Figure 3.34: First stage of Outward Movement

Outward movement starts in second stage with step over of 0.5 mm moving 7.5 mm outward. In this step, outward movement is rotating at constant Z coordinate resulting as shown in [Fig. 3.35]. Remark that to measure any parameters on first and second stage, only clamp holder must be removed from the jig, and the sheet must remain the same position and it must also be replaced at exactly same position on a jig.

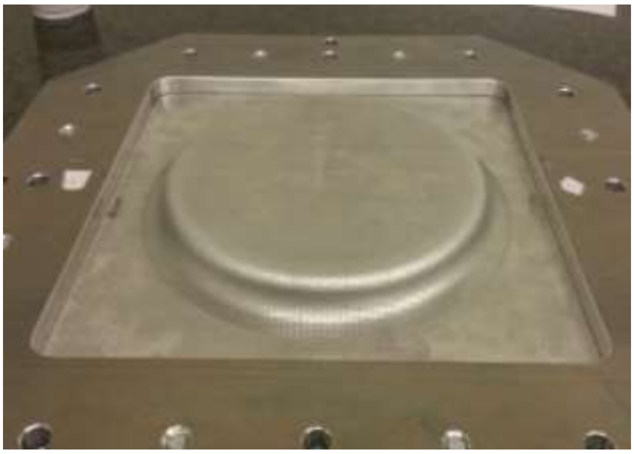


Figure 3.35: Second stage in outward movement

Finally, last outward movement sweeps with the same step over until reaching vertical wall of 16 mm depth as display in [Fig. 3.36]. Stage three could not finish throughout all the code due to fracture occurrence at the corner of transverse area of the sheet. After each stage is done, grid strain must be measured for FFL graph plotting.

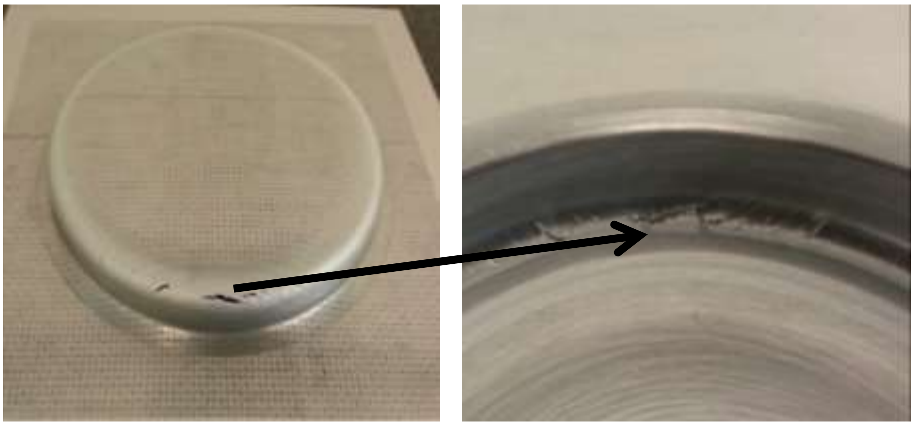
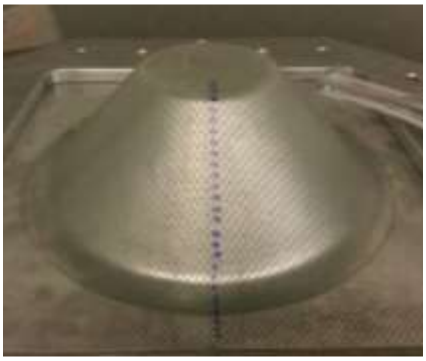


Figure 3.36: Last Stage of Outward Movement

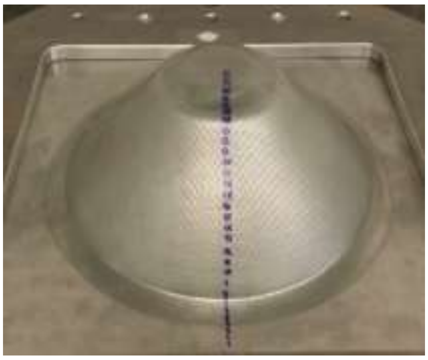
Fracture appeared on both sides of transverse direction on the sheet. It is located at about 15.91 mm depth and has an approximate length of 26.67 mm.

3.5.2.2 Downward & Upward Movement (DDDU)

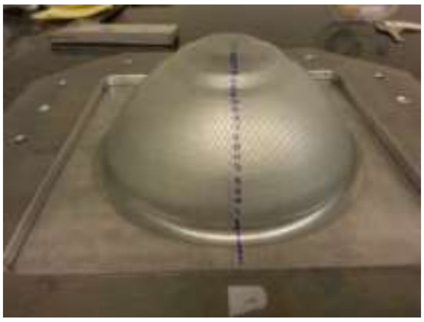
In this test, toolpath is tested to study the influence on wall thickness distribution. As mentioned before in previous chapter, four were created to obtain vertical wall on AA1050 and to have an understanding of multi-stage incremental forming by combining many stages together [see Fig. 3.37].



Stage 1: Downward Movement



Stage 2: Downward Movement



Stage 3: Downward Movement

Stage 4: Outward & Upward Movement

Figure 3.37: DDDU Multi-stage Incremental Forming

3.6 Part Inspection

To analyze finished part [Fig. 3.38], several tests will be taking in order to obtain useful information such as thickness distribution, maximum forming angle for single point incremental forming, surface roughness, forming depth and other general dimension measurement to compare with designed dimension.

Figure 3.38: SPIF finished part

3.6.1 Thickness Measurement

3.6.1.1 Flange Gauge Thickness Measurement

Thickness measurement is performed by using two methods to have a comparison between values. In first place, Flange height thickness gauge [Fig. 3.39a] is used, it is provided by INEGI metallurgy room. Flange thickness gauge is very easy to use and read the value, it has rested ball head tip as for zero setting [Fig. 3.39b]. The equipment has moveable measuring jaw with small LCD monitor to show thickness value in millimeters. First zero setting must be done by placing finished part in place and hold still, next move measuring jaw up and down until reaching measuring area and read the value from monitor.

a. Flange thickness gauge measurement tool

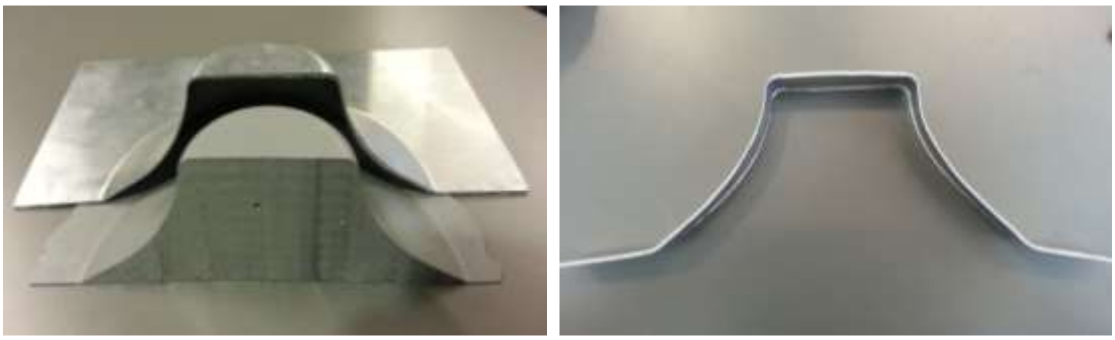
b. Ball tip zero setting and measuring pin tip

Figure 3.39: Flange thickness gauge measurement

Due to short distance between measuring pin tip and the pole that lifted measuring jaw, whole finished part could not fits in and pin tip could not touch exact area for measuring. Therefore, part must be cut by using small saw cutting machine to cut part into smaller pieces [Fig. 3.41b].

Figure 3.40: PROXXON Saw Cutting Machine

Performing sheet metal cutting on saw machine [Fig. 3.40] could cause serious damage to aluminium sheet. Therefore sheet must be filled with resin before cutting [see Fig. 3.41a] to help supporting geometry shape and maintain same thickness. After its solidification, geometry is ready to be cut.



a. Geometry filled with resin after cutting

b. Small pieces after cutting

Figure 3.41: Aluminium sheet for thickness measurement

3.6.1.2 Microscope Thickness Measurement

On the other hand, microscope [Fig. 3.42a] could also be used to measure sheet thickness however this method required very small pieces of sheets. Small sheets will be freeze inside transparent resin [Fig. 3.43a] which makes it easier to hold while looking through microscope and clearly see through. One side of resin shell was polished with sandpaper polishing machine [Fig. 3.42b] until it close to metal surface before measuring. Microscope is connected with camera for capturing a photo with 75x magnify [Fig. 3.43c] and computer monitor to display the picture by drawing a line across surface and obtain distance which refers to thickness. To mark an exact position for measuring, sheet must be mark [Fig. 3.43b] with little scratch on the cross section surface above the point before freezing with resin. Therefore when looking through microscope, area of interest could be notice easily that lay below the scratch point. All apparatus used in this measurement are provided by INEGI materialography room.

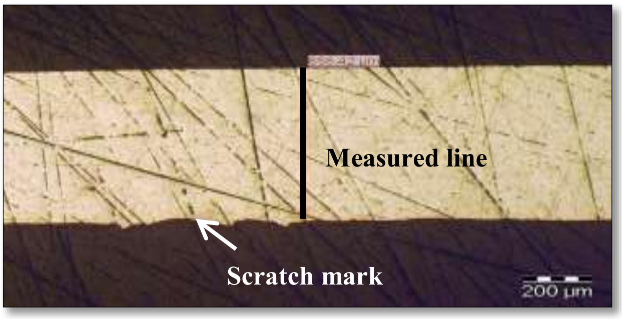
a. Olympus PMG 3 Microscope

b. Sand paper polishing machine

Figure 3.42: Machine used for thickness measurement

a. Sheet freeze inside clear resin

b. Scratch mark on the sheet



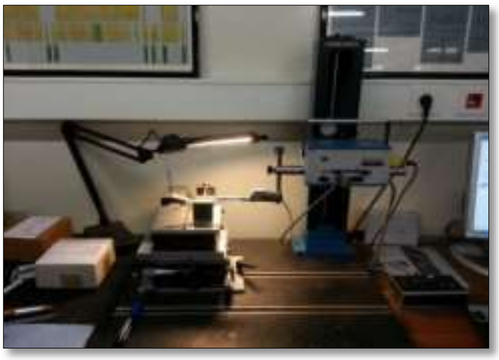
c. Side picture of sheet through microscope

Figure 3.43: Parts used for microscope thickness measurement

3.6.2 Roughness Measurement

To analyze surface finish of incremental forming parts, surface roughness test is performed. Roughness will take part of the inside surface finish area where the tool moves to form shape. First, geometry part is cut into long narrow stripes pieces [Fig. 3.44a] and bends back to straight position. It is necessary to allow measuring pin touching the surface area properly and able the pin to move perfectly on the surface, sheet is mark with color near measuring area to identify position of measuring. A mark will be made: three points each side and one point at the bottom of the shape, total of seven points per geometry. Roughness test is performed in Mechanical Engineering workshop, using HOMMELWERKE LV-50 roughness measurement equipment [Fig. 3.44b].

a. **Prepared sheet for roughness measurement**

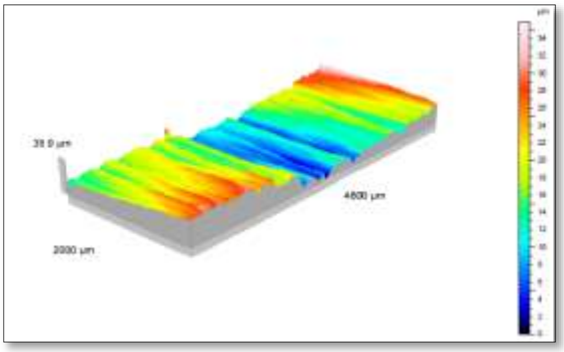


b. **HOMMELWERKE LV-50 roughness measurement equipment**

Figure 3.44: Roughness measurement apparatus

Sheet is clamped straightly with fixtures providing level movement for the pin [Fig. 3.45a]. Machine is connected with computer used to control, to monitor and to collect data during the performance with TMESS (TOPO-TK300) roughness test program [Fig. 3.45c]. Measuring area has a size of 4.8 x 2 mm of each positions, pin will read the value in column direction every 1 µm and move 25 µm to the next column. Each position will take approximately 35 minutes to measure. After finishing, roughness graph will be plotted and 3D surface roughness will be shown as a file [Fig. 3.45b].

a. **Sheet on fixture in straight position**



b. **Roughness result in form of 3D picture and line graph**

c. TOPO-TK300 Program screen

Figure 3.45: Roughness Measurement

3.6.3 Angle Measurement

Obtaining maximum forming angle from single point incremental forming part, maximum forming depth is necessary. Therefore solidwork geometry [Fig. 3.46] was used to perform an angle measurement by drawing vertical line and extends horizontal line to make a contact with curve line; forming angle can be obtained easily.

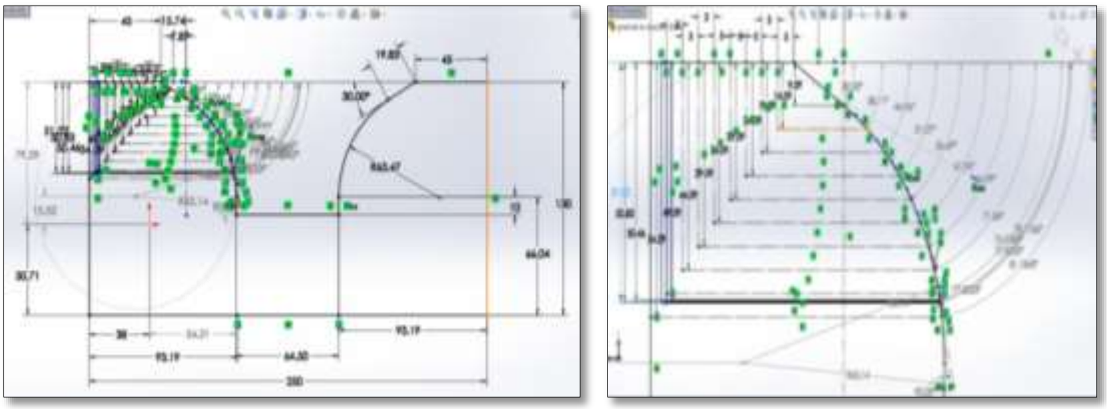


Figure 3.46: Angle measurement using solidwork file

3.6.4 General Dimension Measurement

In the first example of single point incremental forming, many parameters have been measured and compared with CAD designed geometry´s parameter. It is to investigate part forming accuracy and to study a relationship between parameters also. [67] For example maximum part depth, wide and radius of top and bottom part are measure by using Vernier caliper as well as Height gauge measurement [Fig. 3.47].

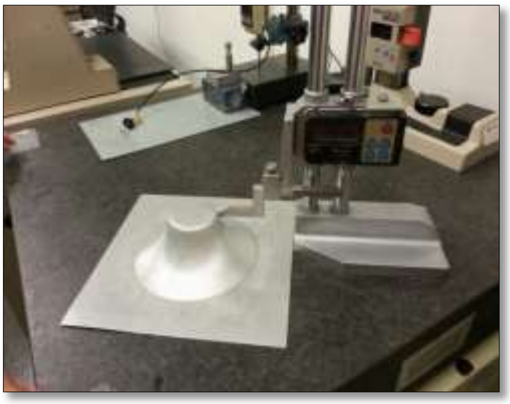


Figure 3.47: Height gauge measurement

3.6.5 Grid Measurement

When sheet metal is formed subjected at various types of stresses, the stress will force non-uniform strain and lead to fracture at the end [24]. Sheet is mark by circular grid pattern, this grid will change the shape due to sheet metal deformation and each grid will deformed differently depending on subjected stress as shown in Fig. 3.48. Grid deform by an amount depending on local deformation experience by sheet metal [7], mostly grid will deform into ellipse unless deformation by pure biaxial stretching as seen in Fig. 3.49.

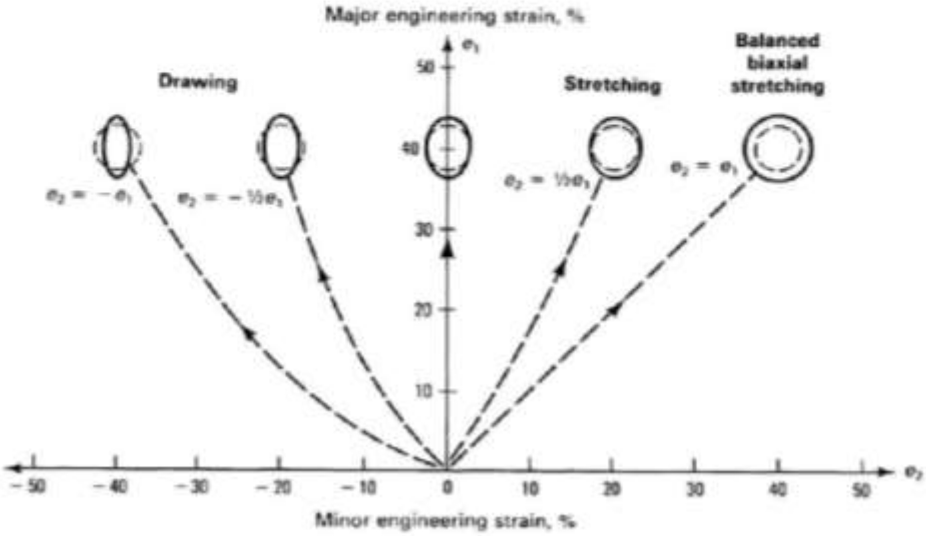


Figure 3.48: Schematic of various major strain and minor strain in FLD [15]

The longest dimension of ellipse grid representing major strain and perpendicular direction to major axis is considered as minor strain [64] as seen in Fig. 3.49.

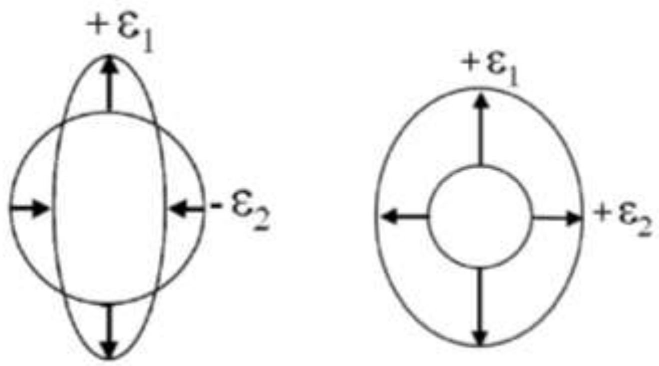
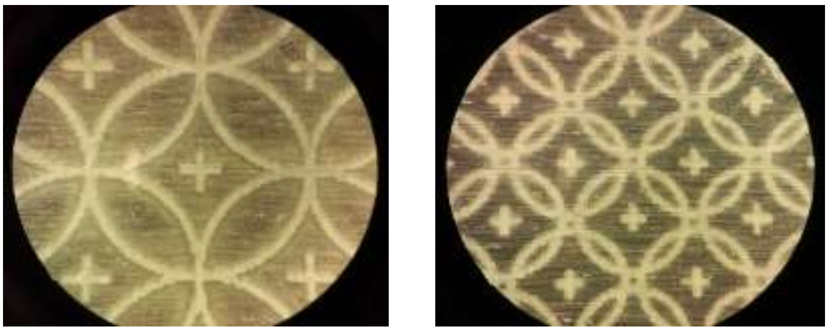


Figure 3.49: Circular Grid Deformed [24]

To measure the gird, microscope is required with careful measure. On the curve profile, using scotch tape could be really helpful to obtain correct dimension. There are two types of grid using in this marking, type one [Fig. 3.50a] and type two [Fig. 3.50b].

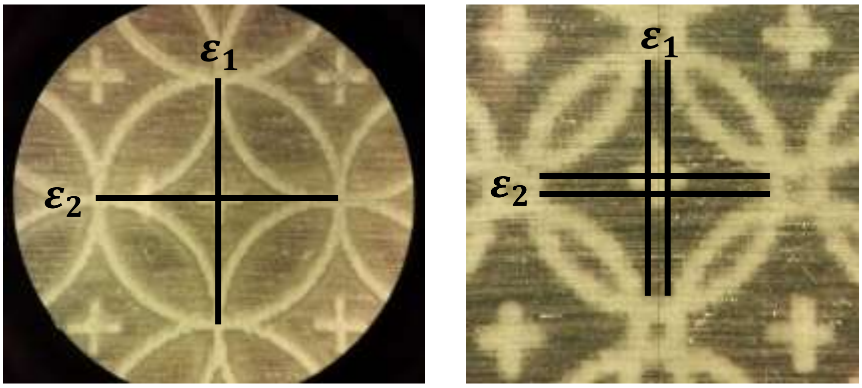


(a) **(b)**

Figure 3.50: Circular Gird used for sheet metal printing

In the first type, two measurements are made: vertical and horizontal direction as shown in Fig. 3.51a. Although type two requires four times measurement per one grid as shown in Fig. 3.51b. Besides, one grid line which covers the area of interest must be selected.

To remark all the grid measure in each stage must be the same circle and same line of grid pattern [see Fig. 3.52] in order to compare the result with previous stage. It is also important to select the area of interest perfectly parallel to microscope´s moveable table during measurement hence accurate dimension could be achieved easily.



(a) **(b)**

Figure 3.51: Circular grid measurement direction

Figure 3.52: Grid measurement along the same line for each stage

CHAPTER 4 RESULT AND DISCUSSION

4.1 Material Characterization

4.1.1 Tensile Test

From the result of tensile test, cloud point of major true strain and minor true strain obtained from tensile test specimen after it has been stretched can be used to find and average point for left side of FFL curve. Moreover Stress-strain curve allows us to use data from elastic region in forming FFL.

The results of tensile test of all six specimens are plotted in Fig. 4.1 and Fig. 4.2. Stress-strain curve is plotted as true stress and true strain using Hooke´s law (Eq.4.1) for an elastic part [11]. However, the true stress-strain curve was obtained by using relation in (Eq.4.2) and (Eq.4.3).

$$\sigma = E\varepsilon \qquad \textbf{(4.1)}$$

$$\sigma = \sigma_{eng}(1 + \varepsilon_{eng}) \qquad \textbf{(4.2)}$$

$$\epsilon = \ln(1 + \varepsilon_{eng}) \qquad \textbf{(4.3)}$$

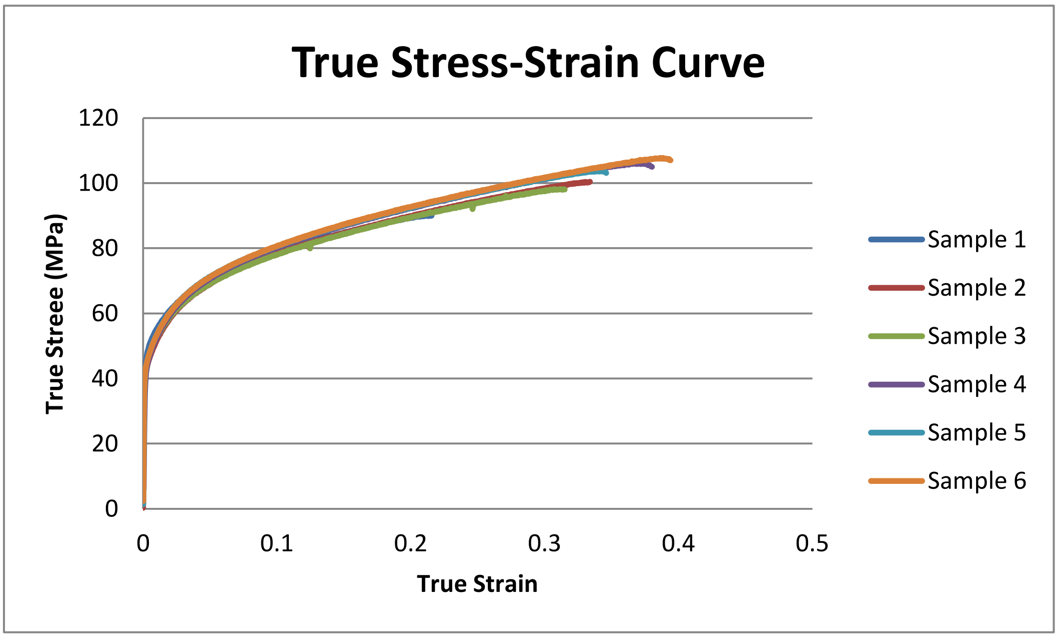


Figure 4.1: True Stress-Strain curve

Table 4.1: Tensile Test Result

Parameters	Yield Stress	Ultimate Tensile Stress	Young Modulus
Al 1050-H111	45.295 MPa	74.795 MPa	70 MPa

Apart from applying the result with Hooke´s law, other studies also present curve fitting with many formulas and one that suit the best with the result appears to be Voce law (Eq.4.4). From the equation, A and B are material constant parameters. The result shows in Fig. 4.2. This law is considered as an example of hardening law, it can be used to model the material behaviour and can be defined as the measurement of how much the resistance of plastic flow increasing as the metal is deformed [11].

$$\sigma = S(1 - Ae^{(-B(\varepsilon+\varepsilon_0))}) \quad \textbf{(4.4)}$$

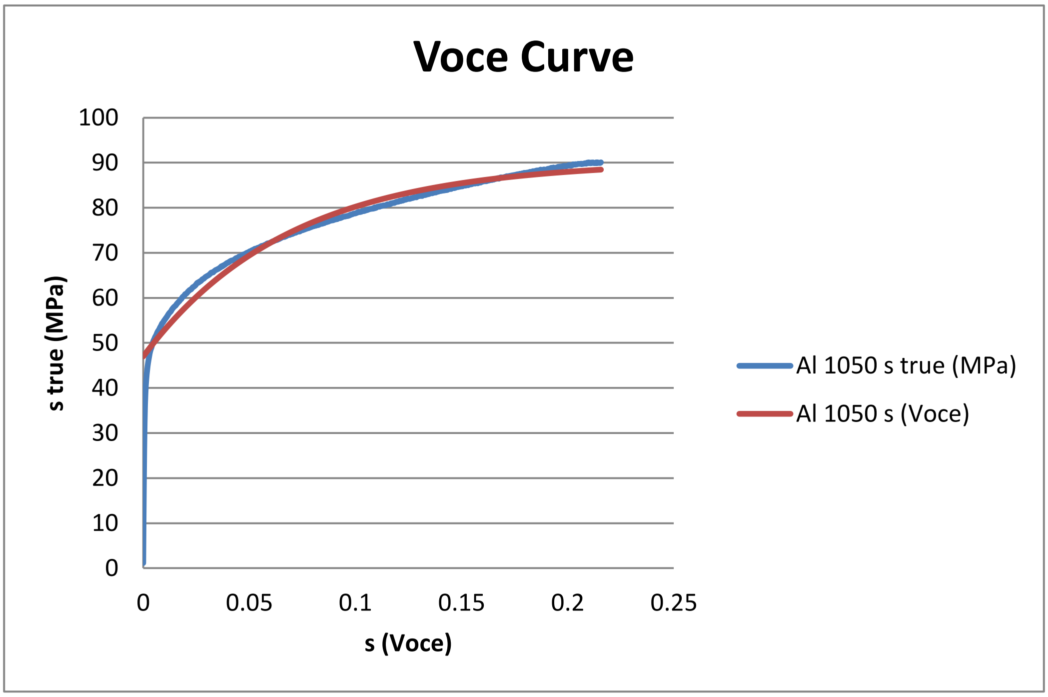


Figure 4.2: Tensile result compare between true curves and VOCE law curve

4.1.2 Forming Fracture Line

Combining the result from tensile test, hydraulic bulge test and in-plain test, Fracture Forming Line can be created from the average value of cloud point of each test. Intersection point between FFL and major strain could be found by conical geometry experimental and/or obtaining from FFL slope (Y = 0.8181X + 1.3358). Experimentally Forming Fracture Line of Al1050-H111 is shown in Fig. 4.4.

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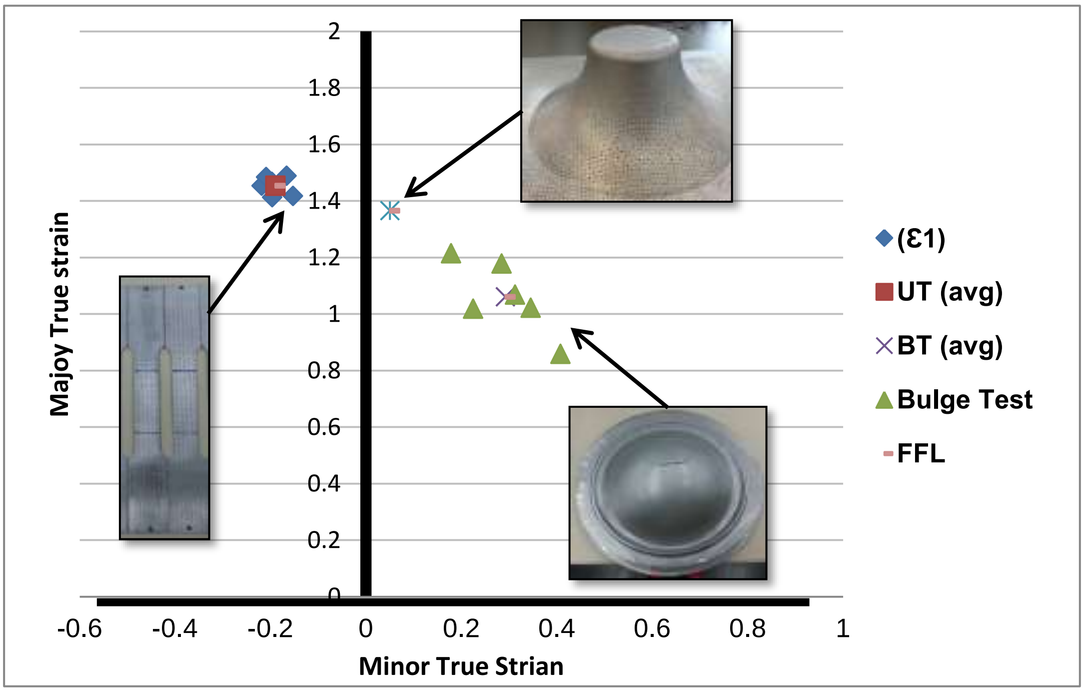

Figure 4.3: Cloud Points of many test forming FFL

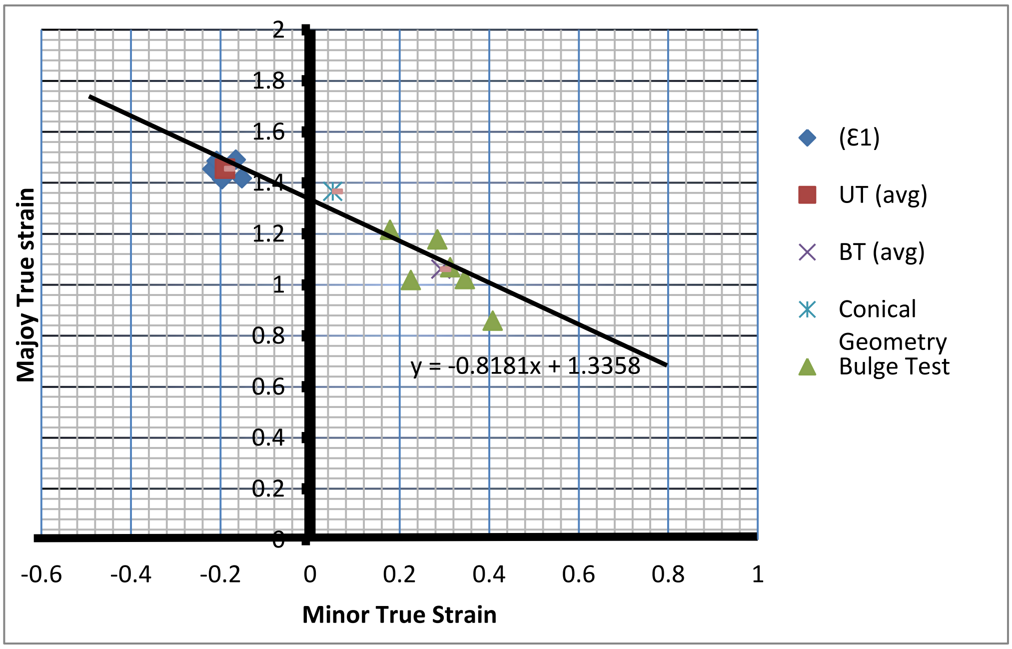

Figure 4.4: Fracture Forming Line Diagram of Al1050-H111

4.2 Single Point Incremental Geometry Analysis

4.2.1 Forming Angle and Fracture Depth

In conical part analysis, an attained maximum depth is at 58.02 mm less than CAD design depth 17 mm. However, pyramid attained depth is maximum at 59 mm less than CAD design depth 19 mm. Therefore, conical and pyramid shape has an accuracy percentage of 77.4% and 74.8%.

During the process, fracture occurred in both shapes but fracture mark of conical shape appeared at deeper depth than pyramid shape. Conical has fracture at 52.2 mm and pyramid has fracture at 50.46 mm. The depth of fracture of each part is able to use to find the maximum forming angle in single point incremental forming. Hence, this result data allows selecting the initial forming angle and choosing the shape for multi-stage incremental forming experiment.

Thus, the result leads to the conclusion that both shapes can be used as a general basic shape for single point incremental forming experiments, as both geometries presented similar maximum forming angle and fracture depth. Nevertheless, performing an incremental forming with pyramidal shape seems to consume less CAD programming code than the conical shape.

4.2.2 Thickness Analysis

4.2.2.1 Gauge Thickness Measurement

Firstly, thickness was measured by using the general gauge thickness measurement method as described in chapter 3. Fig. 4.5 shows the evolution of the average wall thickness with the depth, for a range of 3-48 mm depth. From the result, it can be concluded that the higher the forming angle the lower the final thickness which is accordance to the sine law (Eq. 2.1).

It is obvious that the wall thickness of the conical shape at the same position is slightly lower than that of the pyramidal shape [see Fig. 4.5], which is aligned with the higher forming angle obtained, as more material was used to achieve a higher depth than a pyramidal. Thus the higher formability and maximum forming angle obtained in the conical shape is the result of a more favorable wall thickness distribution.

The deviation found between the thicknesses lines and the theoretical sine law line was expected as the sine law does not take the material properties into account. Nonetheless, both shapes have similar trends lines as the sine law which confirms that single point incremental forming follows the sine law evolution properly.

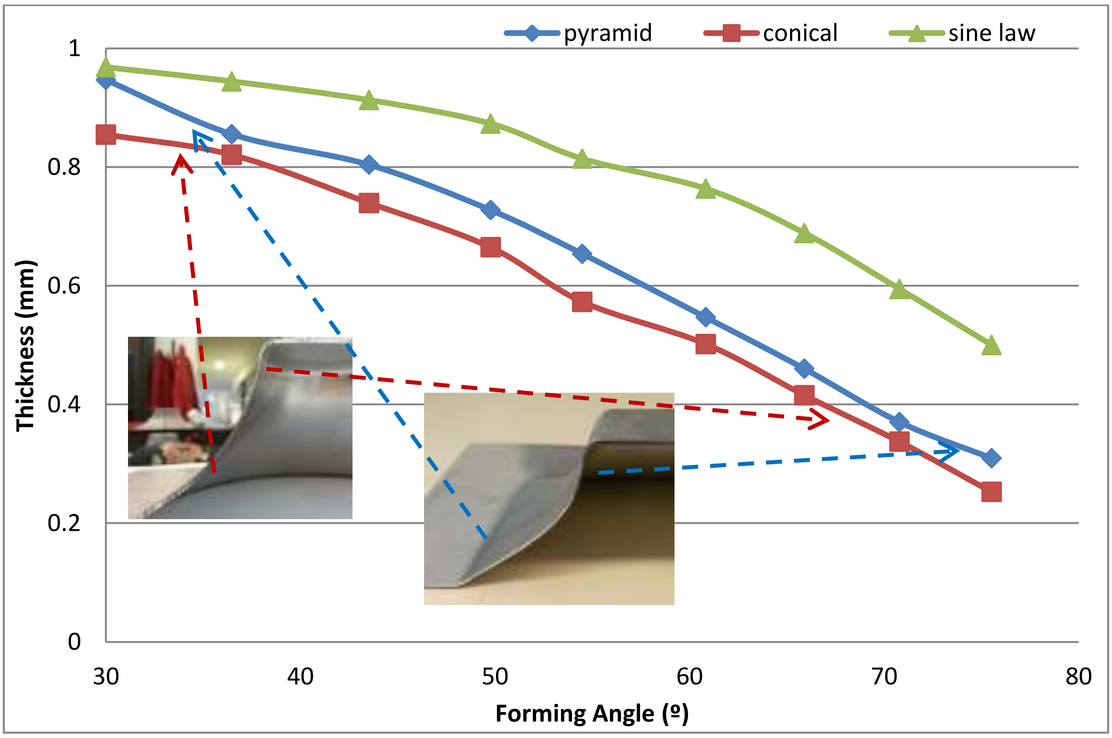

Figure 4.5: Average thickness vs. forming angle in SPIF

4.2.2.2 Microscope Thickness Measurement

Although thickness result from gauge measurement method is well defined, but the analysis was repeated with the microscope as this is a highly accurate measuring method. The result shows that similar values were obtained leading to the same conclusion. Both methods provided a very similar result of thickness distribution, however in pyramid, only 1.8% different in result and 1.15% different in conical shape. Therefore both methods are very feasible and suitable to use for thickness measuring of SPIF.

4.2.3 Surface Roughness Analysis

Surface area used in roughness measurement split into 4 region and the result are shown in Table 4.2 for conical shape and Table 4.3 for pyramid shape. The region of interest for roughness measurement is shown in Fig. 4.6.

Table 4.2: Surface roughness of conical geometry

Surface Roughness	Value
Outer Rolling Region (µm)	1.430
Slippering Region (µm)	0.896
Bottom Region (µm)	0.324
Inner Rolling Region (µm)	0.701

Table 4.3: Surface roughness of pyramid geometry

Surface Roughness	Value
Outer Rolling Region (µm)	1.447
Slippering Region (µm)	0.680
Bottom Region (µm)	0.346
Inner Rolling Region (µm)	0.507

Table 4.4 concerns about average roughness of SPIF and the result shows that bottom part corresponds to sheet original property presented the lowest surface roughness, duet to no contact with the tool during the manufacturing. Oppositely, the outer rolling region presented the largest surface roughness value subjected to constant tool contact.

The significant tool tip wear could also contribute to the creative of scratch on the sheet surface. On the other hand, slippering region and inner rolling region presented lower surface roughness, as the contact with the tool was restricted to the side surface of the tool, with lower wear.

Table 4.4: Average Surface Roughness Result

Region	Sa	Avg. Ra
Outer Rolling	1.42	1.445
Slippering	1.07	0.9155
Inner Rolling	0.759	0.7125
Bottom	0.53	0.324

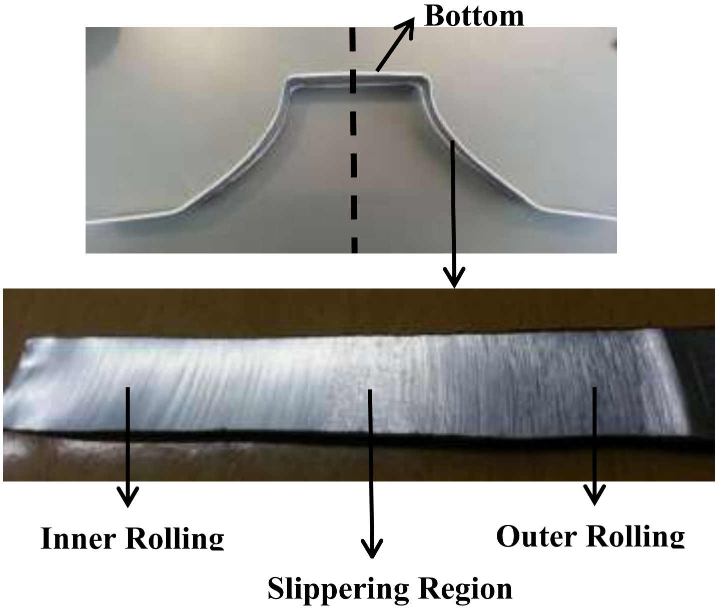

Figure 4.6: Surface roughness area of interest

4.3 Multi-Stage Incremental Forming Analysis Result

4.3.1 DOO Movement

4.3.1.1 Thickness Analysis

As shown in Fig. 4.7, the location at the corner under large amount of stretch force from the tool radius (point number 6) presented the lowest thickness value in every stage. Outward movement in stage 2 at constant Z coordinate has drawn only some material from the side of the wall and affects significantly the wall stretching.

In stage 3, outward movement with 1 mm step down resulting in stretch of more material from the wall and from the bottom of the parts causing a significant lower thickness at the corner (point 6) Thus later step was seen not to be effective in redistributing the sheet thickness from the bottom part.

In fact the sheet was seen to fracture before finishing the stage 3 which higher step down should be tested in order to obtain a significant thickness distribution from the bottom to the side.

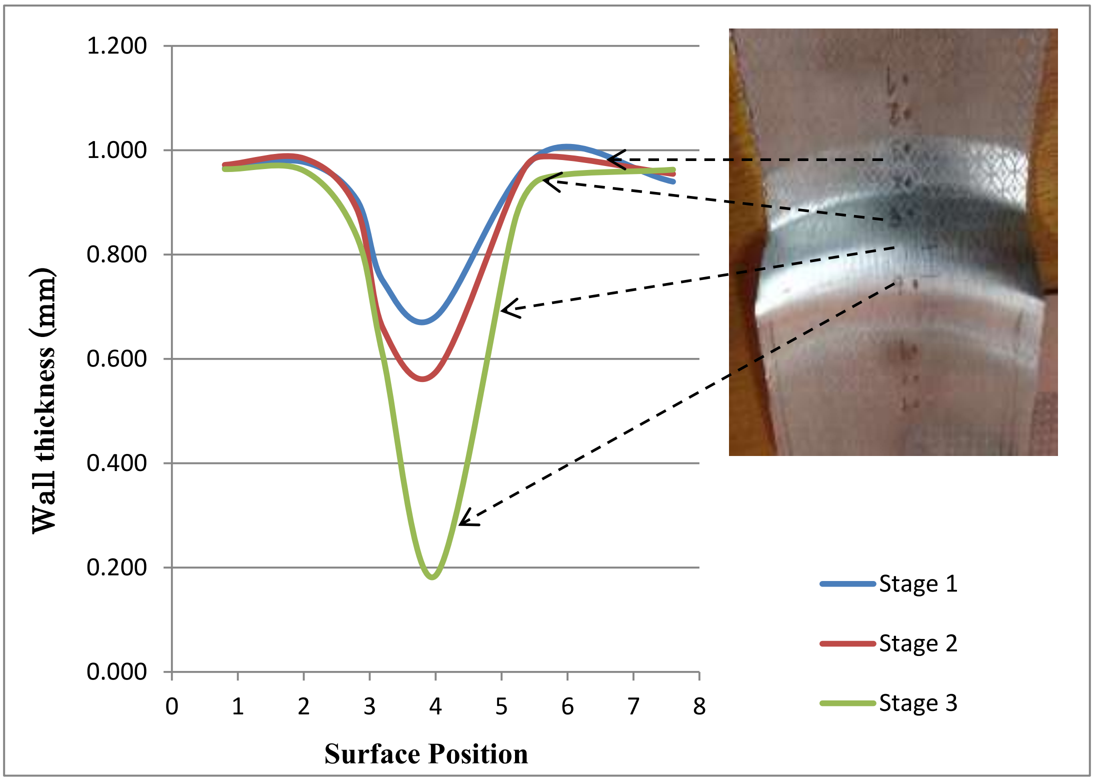

Figure 4.7: DOO Part Thickness Distribution

4.3.1.2 Strain Analysis

Stage: 1

Stage: 2

Stage: 3

Stage 1: Downward 45º Angle

In stage 1, 45º was chosen as the initial angle. The resultant strain level is presented in Fig. 4.8. Strain in this stage is distributed evenly near plane strain.

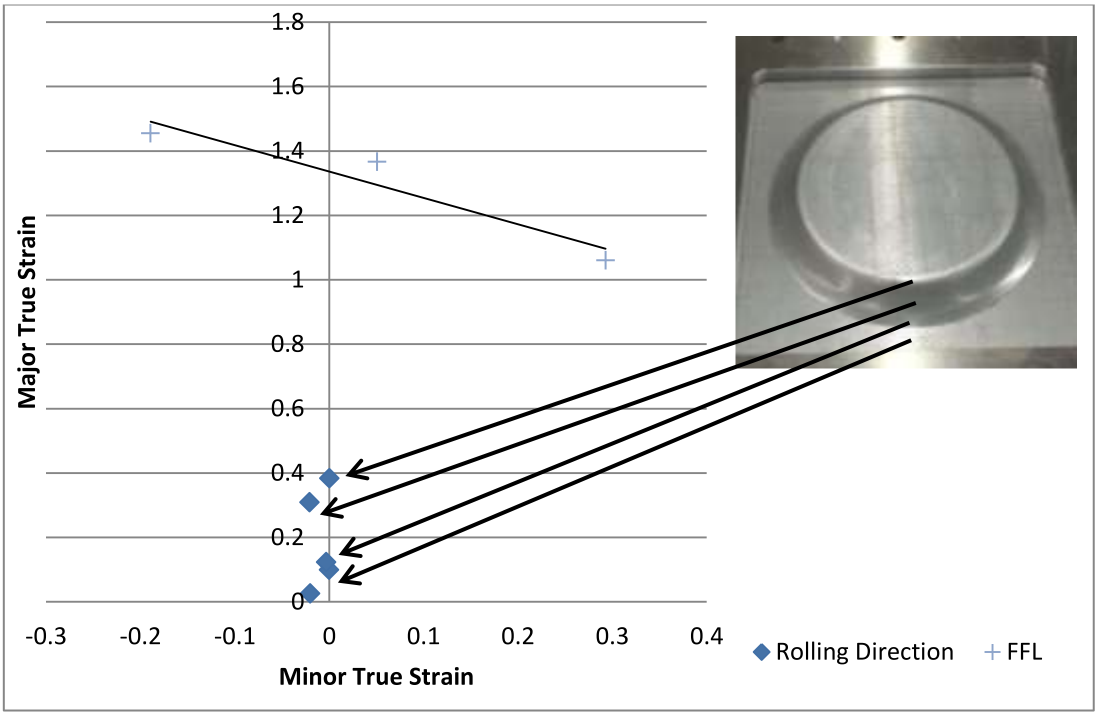

Figure 4.8: FFLD of first stage in outward experimental

Stage 2: First Outward Movement

The subsequent stage 2 [Fig. 4.9], shows higher deformation particularly at the bottom corner which again distributed in plane strain.

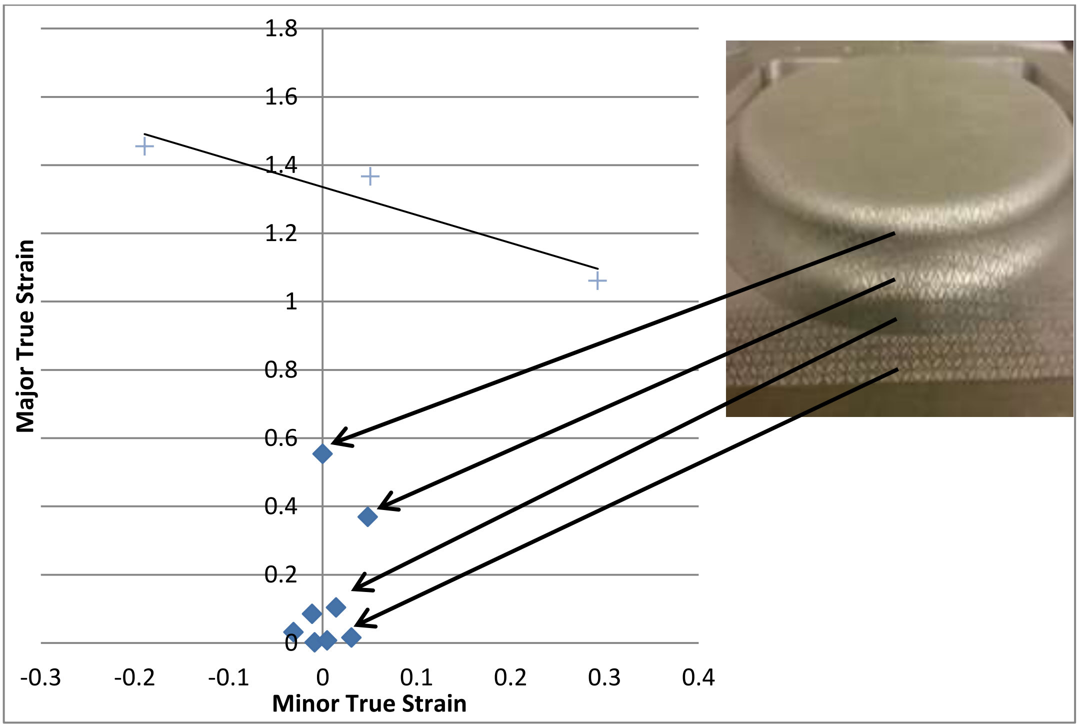

Figure 4.9: FFLD of second stage in outward experiment

Stage 3: Second Outward Movement

In stage 3 [Fig. 4.10], fracture occurred at the bottom corner (point 6) in transverse direction, subjected to multiple stretching stages. Besides, less material is drawn from the side of the wall only from the bottom resulting in less deformation at point 3 to point 5.

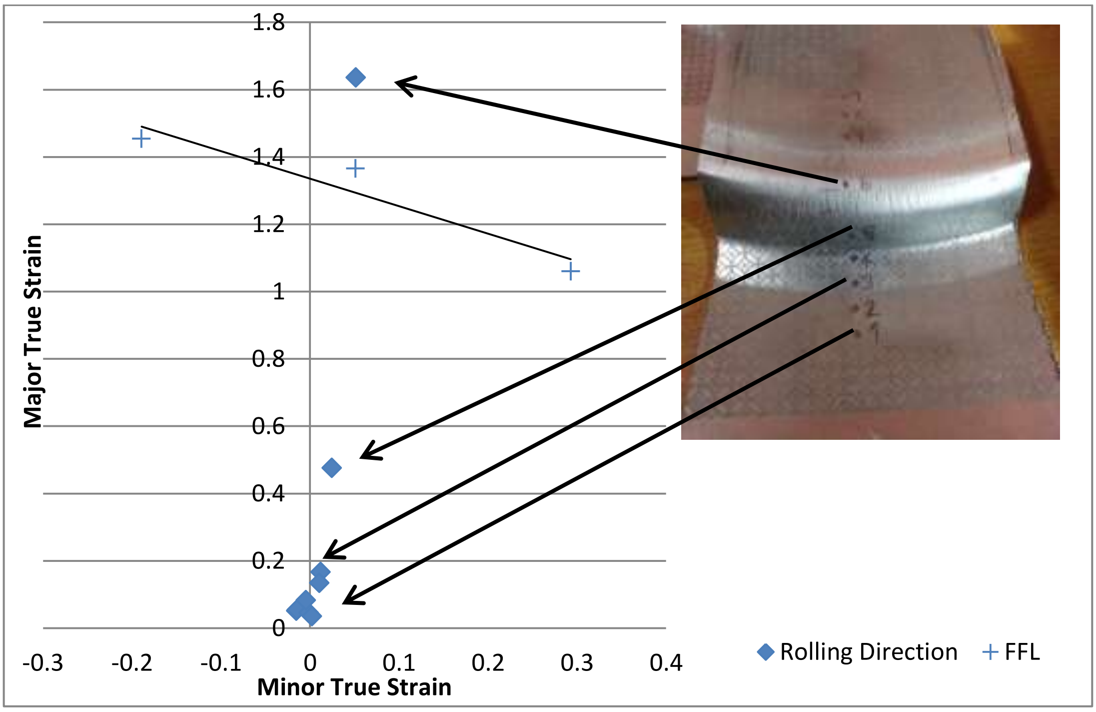

Figure 4.10: FFLD for third stage of outward experiment

4.3.2 DDDU Movement

4.3.2.1 Thickness Analysis

Stage 1: Downward 45° Angle

The thickness distribution show in Fig. 4.11 shows constant thickness value at the inclined wall of 45° and a value close to the initial thickness near the bottom.

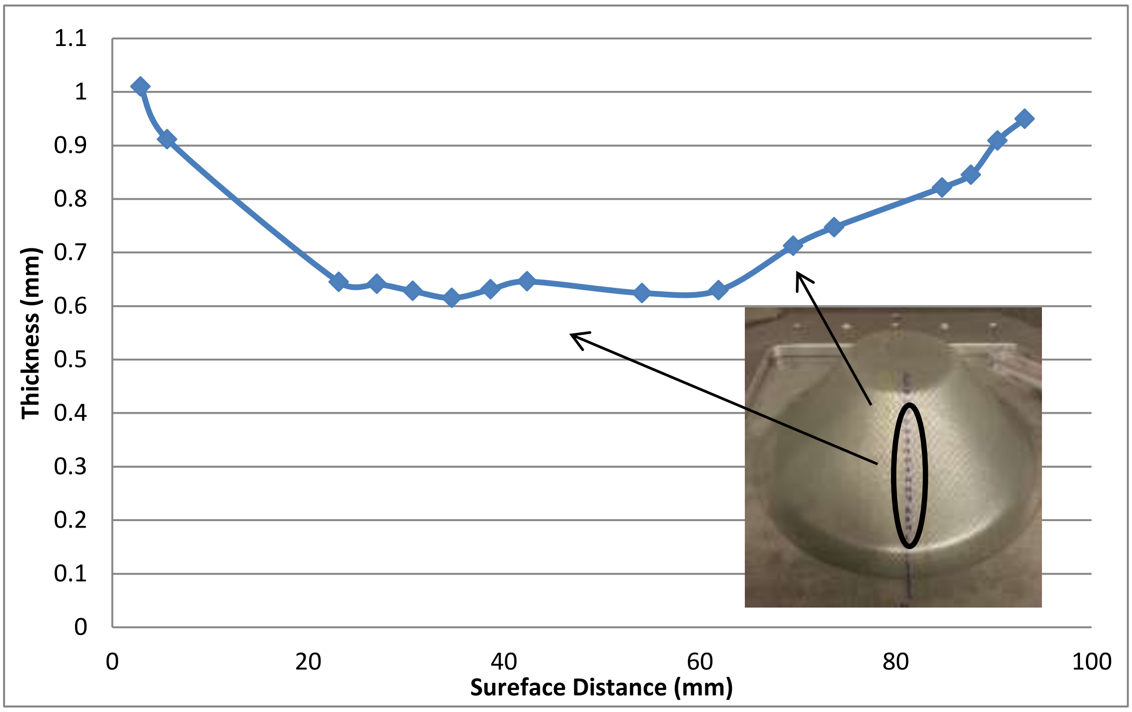

Figure 4.11: Stage one of DDDU Multi-stage incremental forming

Stage 2: Second Downward Movement (Curvature: 225.5 mm)

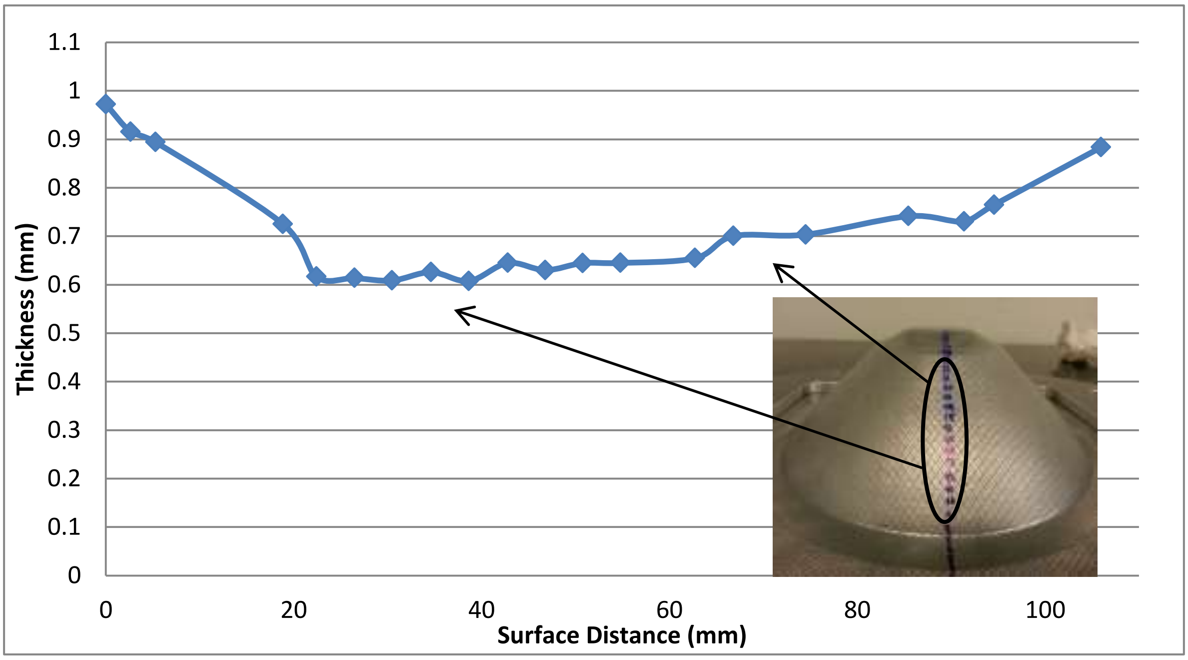

Figure 4.12: Second stage of DDDU Multi-stage incremental forming

Thickness in stage 2 [see Fig. 4.12] does not presented significant different thickness value. The forming angle applied in this stage 2 should be higher to promote closer approach to vertical wall and to prepare the material to be drawn in the next stage.

Stage 3: Third Downward Movement (Curvature: 95.5 mm)

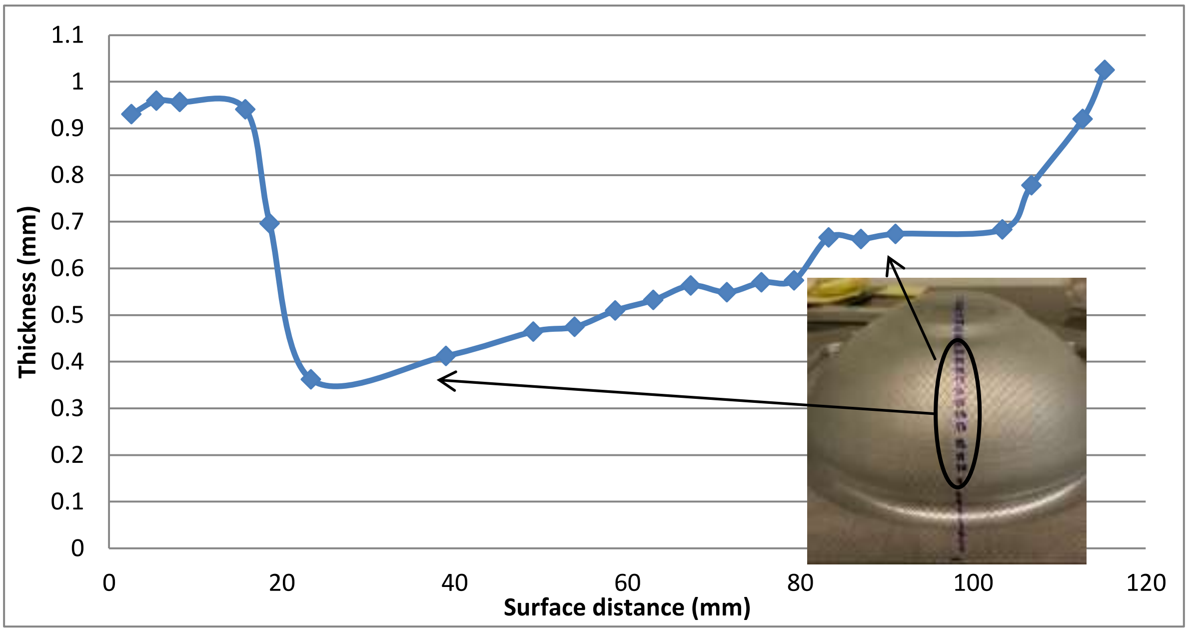

Figure 4.13: Third stage of DDDU Multi-stage incremental forming

On the other hand, stage 3 shows extremely lower thickness value on the area of curvature profile, cause by the repeat tool movement in that area to expand and stretch more material close to vertical angle. The minimum thickness value after this stage was seen in the range of point number 9 to point 20 as shown in Fig. 4.13.

4.3.2.2 Strain Analysis

Stage 1 *Stage 2* *Stage 3* *Stage 4*

Stage 1: Downward 45º Angle

In stage 1, the maximum strain value of strain was obtained at the bottom corner of the shape where maximum stretch occurs as seen in Fig. 4.14. The cloud points comes inclined wall angle.

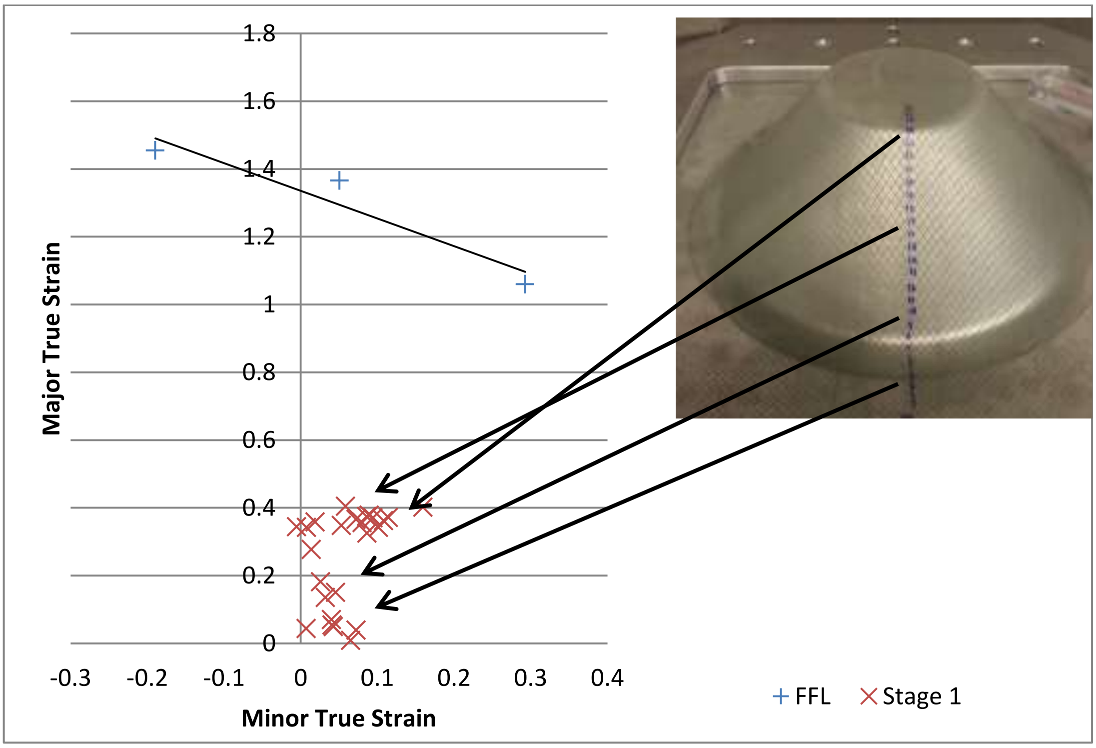

Figure 4.14: FFLD for first stage of DDDU multi-stage incremental forming

Stage 2: Second Downward Movement (Curvature: 225.5 mm)

For the subsequent stage 2, the highest deformation takes place at the side of the profile [see Fig. 4.15] after the second stretching step. However, this stage was meant the stretch along the wall area but due to the excessively low angle increment, the deformation was not significantly different from that obtained in stage 1.

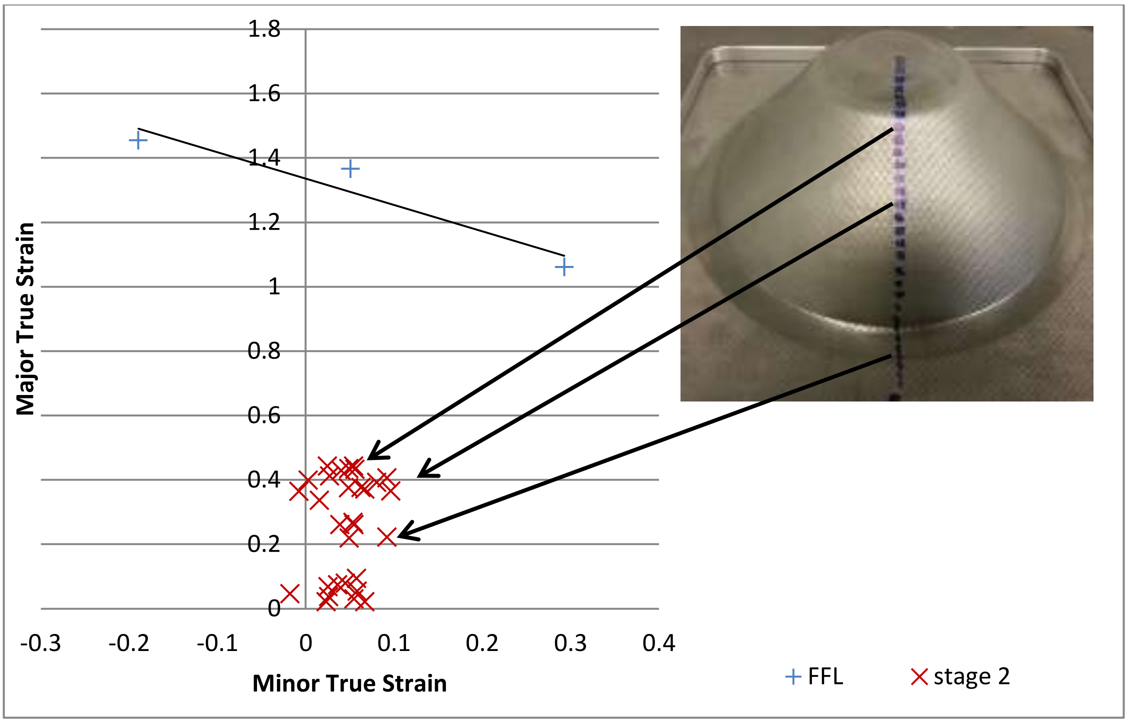

Figure 4.15: FFLD for second stage of DDDU multi-stage

Stage 3: Third Downward Movement (Curvature: 95.5 mm)

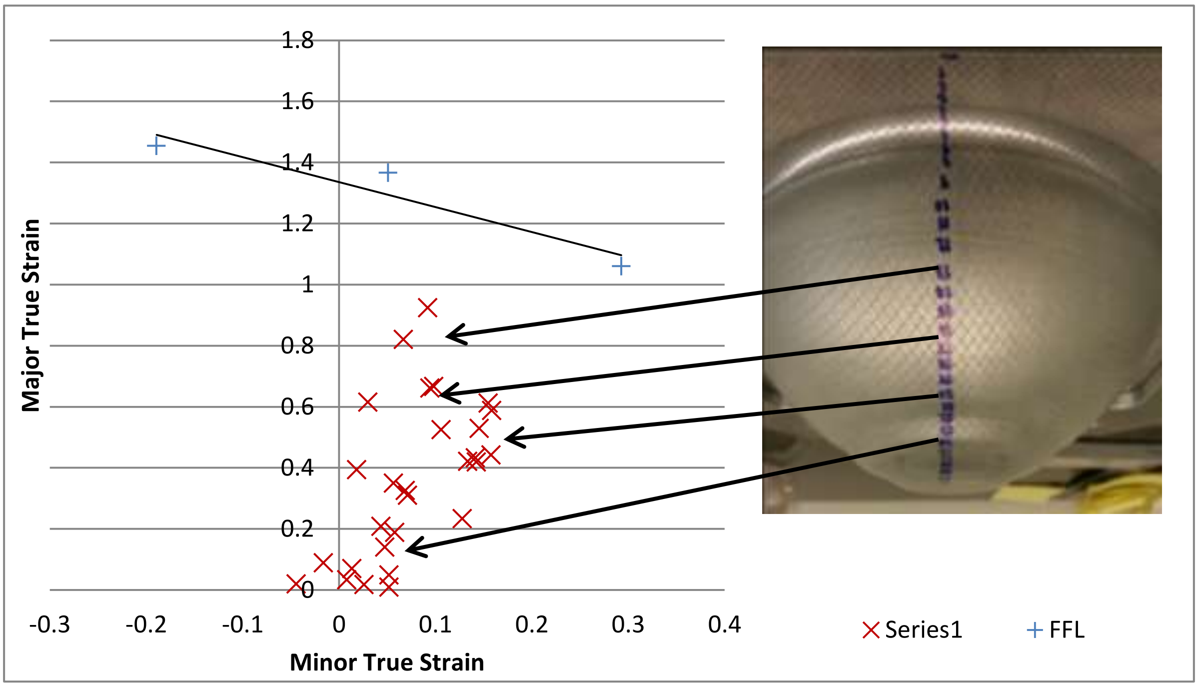

Figure 4.16: FFLD for third stage of DDDU multi-stage incremental forming

In stage 3, the angle increment was expected to promote the shift of more material from the top to bottom. In fact, more deformation was seen to occur at the side of the shape as shown in Fig. 4.16. The lowest deformation appeared below the residual cone, determined by the lower deformation induced in stage 2 and 3.

Stage 4: Outward and Upward Movement

Two types of movements were proposed in this stage: outward and upward movements. Outward movement was performed at 67 mm depth, but in different forming angle and tool that is proposed by Camara [23]. The result shows that fracture was achieved at the bottom of the cone. Fracture displayed in Fig. 4.17 was obtained before completing the full outward movement showing exceed deformation at the bottom part of the shape completing all outward movement and before reaching the stage of upward movement regarding to too much deformation at the bottom part of material.

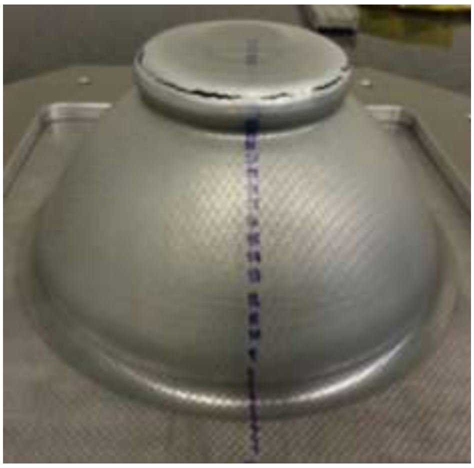

Figure 4.17: Fourth stage of DDDU multi-stage incremental forming

CHAPTER 5 CONCLUSION

The work developed was aimed to analyze the material formability limit of aluminium alloy 1050 and mechanism of deformation of the sheet metal during conventional and multi-stage single point incremental forming. The experiment performed in this work shows the result as expected and agree with previous research proposed by Silva[20].

The result of single point incremental forming also shows that conical shape can perform a higher forming angle than pyramid shapes, being the most preferable shape for conventional incremental forming method. This result is in agreement with Jeswiet [52] research. Moreover, material has follows sine law properly during an incremental forming process as expected.

Both method of thickness measurement gives similar result. The percentage difference (1.8%) between the two methods is very small and confirms that the two methods gave almost the same result. In addition, given a confidence interval of 95%, it was found that the measurements taken for the pyramid by using flange gauge and microscope gave a marginal error of $\pm$0.019 mm and $\pm$0.013, respectively. This proves that the measurements taken by using microscope gave a more consistent value. On the other hand, the measurement results for a conical object seemed to have given more consistent results. By evaluating the results with 95% confident interval, it was found that the margin of error from using a flange gauge and a microscope were 0.009 and 0.011, respectively. In this case, the consistency of the results obtained from the flange gauge was better than that obtained from the microscope.

Therefore, the margin of error from the results obtained from both methods shows that the values overlap. However, it can be concluded both instruments can perform the measurement to an acceptable amount of precision and accuracy.

The inconsistency of the results will mainly come from human error. It was possible that the object was not placed at the exact same position each time that the measurements were taken.

Outward movement was performed by replicating Camara[23] work in order to have a better understanding of the influence of toolpath parameter and to study the trajectories used for obtaining vertical walls. However, some parameter such as forming angle considered in each stage is different from previous work. Since then the result of each stage shows the improvement of deformation and decrease in wall thickness along the profile as same as the previous research. Nonetheless, the result does not attaining the same final part as previous work due to the occurrence of premature failure. However, result allows concluding that outward movement distributes material from the bottom in a small amount, which depends on the angle increment. Therefore, more outward movement should be examining with more angle of increment, more previous stage before outward movement should be added as well as more depth for outward movement to obtain complete vertical wall.

Regarding the DDDU multi-stage incremental forming that was proposed in order to also duplicate Camara [23] work, the main objective was to study the influence of different toolpath by creating more stages with different movement. With this work, it was expected to obtain conical shape with vertical wall that has already been achieved before. However some initial value for example forming angle, toolpath and forming tool types are different from previous work. These differences lead to failure during processing to achieve the desired part, fracture appearing in last stage. Furthermore, this experiment leads us to conclude that more material is shifted and thickness is redistributed by using multi-stage incremental forming and more stages of DDDU give better thickness distribution and draw material deeper than DOO movement and SPIF.

Nonetheless, more research and experimental must be done to investigate more strategies and possible different toolpath to obtain vertical wall.

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