ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF MECHANICAL AND VEHICLE ENGINEERING

Investigation the Effects of Process Parameters on Single Point Incremental Forming Processes on Aluminum (1050) Sheet

A Thesis Submitted to School of Graduate Studies of Adama Science and Technology University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Manufacturing Engineering

PROGRAM: MANUFACTURING POST GRADUATE

BY:
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(GSR/03014/07)

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Declaration

I, Dawit Desalegn hereby declare that the thesis entitled **"Investigation the Effects Of Process Parameters on Single Point Incremental Forming Processes on Aluminum (1050) Sheet"** submitted to the Adama Science & Technology University, Adama, in partial fulfillment of the requirements for the award of the degree of Master of Science in Manufacturing Engineering, School of Mechanical, Chemical and Material Engineering is a record of original and independent research work done by me under the guidance of adviser **Dr. Perumalla Janaki Ramullu** (associate professor) and co-adviser **Mr. Dagmawi Haile**.

It has not been presented as a thesis in any other university and all sources of materials and supporters used for this thesis are accordingly sited and acknowledged.

Dawit Dessalegn Date signature

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This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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Mr. Dagmawi Haile(Msc.) Date signature

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BY

DAWIT DESALEGN

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Abstract

Now day there is an increasing demand in metal forming processes in which one is sheet metal forming process for lots of applications. Sheet metal forming have many processes out of these incremental forming is an emerging technology, in which forming was done by CNC (computer numeric control) milling machine. So that the forming process was step by step gradual forming process. Unlike to two the point forming process and spinning processes single point incremental forming process is die-less in nature. Incremental forming provides competitive alternative for economically and also effective in fabricating low volume products even has important too in mold making and pattern. This process locally deforms sheet metal using a moving spherical tool head and the shape is governed by the path of the tool. The objective of this thesis is to study on truncated pyramid of products by maintaining its formability avoiding cracking and the optimum forming condition through simulation and modeling. Methodology aspect was done using Master Cam for generating the tool path and the modeling was done by Solid work software. Once tool movement was created using software Master Cam X5 which simulate the path of the tool and generate a code command which can understand in the CNC three-axis milling. The formability was analyzed by using finite element software ABAQUS 6.13. The simulations were performed on different parameters like sheet thickness, tool diameter, step depth, spindle rotational speed. From simulation result of we obtain equivalent von misses stress and equivalent plastic strain. We compare the result with other processes and compare with the ultimate stress value of aluminum (1050). Strain distribution across the mid-section and edge section on the deformed sheet from each experiment we conduct. The blank material used in the forming process is aluminum (AA1050) and steel (1040) for tooling. The product produced is truncated pyramid having dimension having square base of side of 200mm with depth up to 4cm and having fillet at corner. After completing this thesis, it identified parameters affecting the process and optimize the parameter for better forming process.

Keywords: *Formability; SPIF; ABAQUS; Master CAM; solid work; three-axis CNC milling.*

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Abbreviation and Nomenclature

		Remarks
ISF	Incremental Sheet Forming	
SPIF	Single Point Incremental Forming	
TPIF	Two point incremental forming	
CAD	Computer Added Design	
CAM	Computer Added Manufacturing	
FLD	Forming Limit Diagram	
CNC	Computer Numerical Controller	
DT	Deforming tool	
t_i	Initial sheet thickness	mm
t_f	Final sheet thickness	mm
Δz	Incremental step down size	mm
α	Draw angle or wall angle	
Al	Aluminum	
DOF	Degree of Freedom	
FEA	Finite Element Analysis	
RPM	Revolution per minute	
3D	Three Dimensional	
σ	Engineering Stress	MPa
ϵ	Engineering Strain	
ϵ_t	Thickness Strain	
n	Strain Hardening Coefficients	
E	Modulus of Elasticity	GPa
ν	Poisson's ratio	
ρ	Mass Density	
S	Stress components	
PEEQ	Equivalent plastic strain	
U	Translations and rotations	
Rf	Reference point	
B.C	Boundary condition	
S4R	Four node finite-strain elements	
R3D4	three-dimensional rigid surface elements	
C3D8R	8-node linear reduced integration	
l	Length	m
m	Mass	kg
T	Time	s
F	Force	N

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CHAPTER ONE

1.1 Introduction

Nowadays, many industrial sections use forming processes such as deep drawing, spinning and stamping in order to manufacture sheet metal components with high productivity. These two forming process are similar with the incremental sheet forming ISF shown in Fig 1.1. All process obeys theory of metal forming, which is constant mass principle that means thickness reduction compensated by stretching. The need for a flexible technology that is also viable for small and medium-sized enterprises. Incremental sheet forming is recent in a computer aided manufacturing process for manufacturing sheet metal to form a conical and pyramidal shaped products. It uses computer numeric control (CNC), changing the cutter by the forming tool that is spherical or ball shaped tip [1].

The process of ISF is based on the layered manufacturing principle, where the model is divided into horizontal slices. The numerically controlled CNC tool path is prepared using contours of these slices. In the process, the universal spherical forming tool is moved along the NC controlled tool path as follows [2].

The conventional sheet metal forming process need part dependent tooling, which costs in terms of time and money. Due to these factors along with increasing variants, variety in the sheet metal fabrication, highly flexible forming processes are being developed. Hence the process offer higher flexibility reducing the product development greatly and making it suitable for low volume production [1].

ISF and spinning are closely related both are Incremental Sheet Forming processes in which forming process is done step by step with this aspects in common, but there are some fundamental differences. In conventional spinning the blank edge is moving inwards, and the material thickness is kept more or less constant. In shear spinning the blank edge is not moving inwards and the sheet thickness are reduced considerably .As in flow forming, the final wall thickness is determined by the distance between the tool and the mandrel. Basically, the mold determines the final shape. [1]

Eventually spinning process is more likely with SPIF but they are different in that SPIF uses CNC milling machine while spinning process uses lathe machine. In addition to this SPIF can form many complicated product but spinning process used for symmetric circular products [1].
One significant outcome of SPIF is the ability to form asymmetric shapes at low cost, without expensive dies incremental sheet forming (ISF) can be interpreted in different ways [1].
In the last that separates symmetric spinning from ISF processes are purely a consequence of the introduction of CNC mills and CAD software with tool path postprocessors. Fig.1.1 shows forming processes of single point forming processes (SPIF), two points forming processes (TPIF) both performed using three axis CNC milling machine and pressing with male die and female die [3].

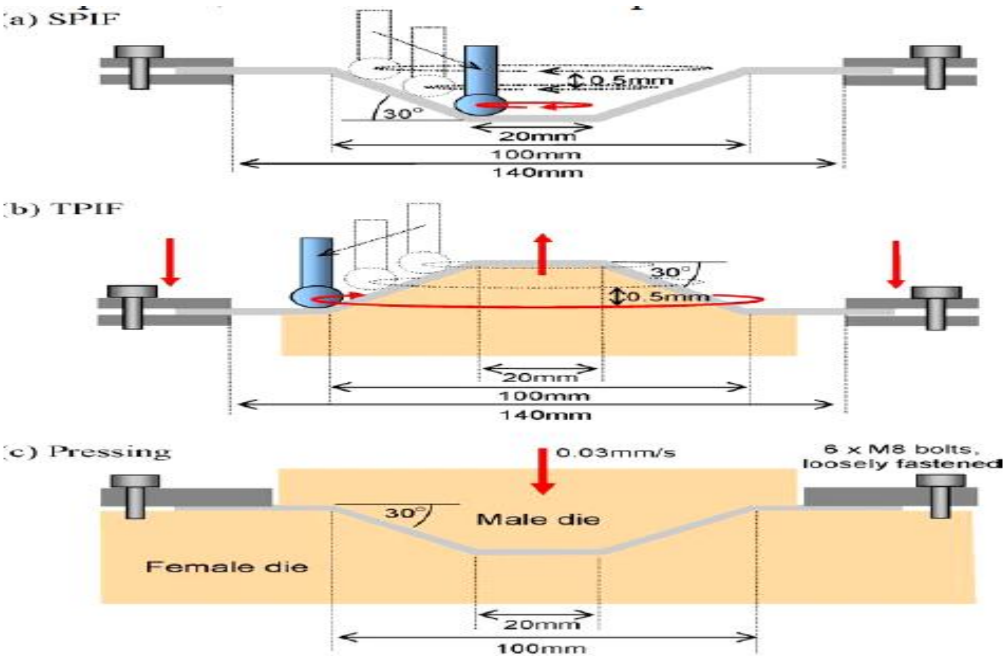


Figure 1.1 a) SPIF b) TPIF C) pressing forming

Elements of Incremental Forming Process Incremental forming is a recent technology for deforming sheet metals by the application of step-by-step incremental feed to a deforming tool. For the production of parts by conventional sheet forming techniques, dedicated tools are required. The dedicated tools are complex 3D design and thus are expensive. The design of tooling (die and punch) for complicated shapes is very difficult and costly [3].

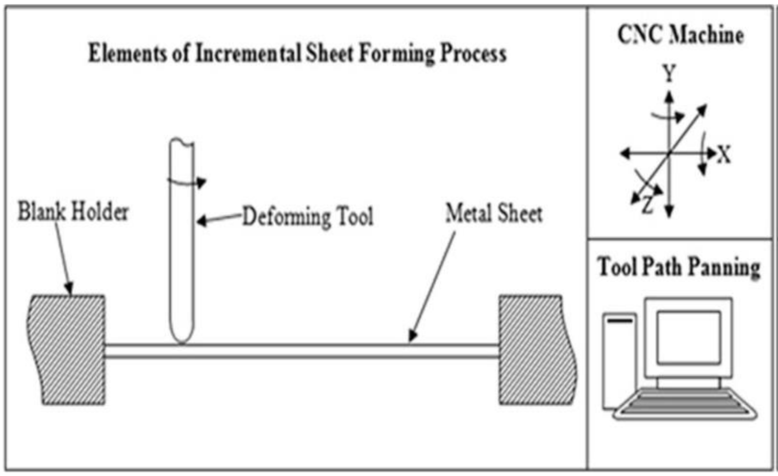


Figure 1.2 Basic elements of ISF

There are four basic elements of an ISF process as shown in Fig. 1.2 a sheet metal, a blank holder, a single-point forming tool or DT, and CNC machine is shown in Fig. 1.2 [3].

A CNC controller having capability for controlling individual 3 axes can be used to control the movements of the DT. The tool path needs to be optimized and a free run is taken before performing the actual manufacturing on the sheet metal in order to ensure the proper functioning of the machine. [3]

1.2 Statement of the Problem

Conventional sheet metal forming processes require large batch sizes (mass production) because these processes require more energy costs and high investment in equipment and tooling (i.e. machine-tools, molds, dies, jigs and fixtures). The need for a high potential economic payoff for rapid prototyping applications suitable for flexible and small quantity production fulfilling this gap in metal forming processes. The problem in this thesis arises from the need to develop truncated pyramid using single point incremental metal forming process using three axis CNC milling machines and by changing only the cutting tool by forming tool that means ball or spherical tip end is used. SPIF process is capable of forming different operation to product development without the need of preparing the die. It is clear that SPIF process is having significant role in the metal forming industries. From this thesis, we would like introduce this concept to Ethiopian metal forming industries. From this thesis, we would like introduce and fill the gap in to Ethiopian metal forming industries.

1.3.1 General Objectives of the Study

The aim of this thesis is to understand the effect of process parameters on single point incremental sheet metal forming processes and to identify optimum conditions for single point forming process.

1.3.2 Specific Objectives of the Study

- Introduce the concept of single point incremental forming process in metal forming industry in Ethiopia.
- Model the complete SPIF process arrangement including tool and blank holding device as well as of the product obtained from the end of SPIF using **solid work**, **ABAQUS** and **Master CAM** modeling software.
- Develop the G-code and M-code using Master CAM code generator to enable CNC machine understand and undergo the predefined path sequential command according to the product to be formed in SPIF.
- Determine the limiting values of parameters such as tool diameter, rotational spindle speed, distance or gap of the tool with fixture and incremental depth of the forming that affect the forming of SPIF.
- Stain distribution of the formed sheet with respect to corner and mid-section of the pyramid.
- Identify the parameter which is sensitive to the incremental forming process compared to other parameters.

1.4 Scope and Limitation of the Study

This thesis work conducted only for single point incremental forming process not includes other ISF processes like two points incremental or multi point incremental forming process.

- It focuses mainly on the forming of truncated pyramid shaped bodies having fillet at the edges. Since spinning process used only for conical shaped products due to this Pyramidal shape was used.
- Forming process done using 3-axis computer numeric milling and analyzed using the help of ABAQUS 6.13 FEM with dynamic explicit.
- The material used here in the paper is aluminum (AA1050) alloy for the blank material which

is suitable for the food containing and processing and steel (1040) used for the punch tool.

1.5 Significance of the Study

The need for single point incremental sheet metal forming is now a day widely used in forming technology. It is applicable in many home, medical appliance, automotive spare parts and other components.

This thesis is helpful for manufacturing industries since the technology is easy and adaptable to 3 axis milling machine, this technology aid society for better use different manufacturing various equipment's.

Aerospace Industry: Instrument panel, body panel, passenger seat cover, etc.

• Automobile: Door inner/outer panel, hood panel, engine cover, etc.

• High customized products: Denture plate, ankle support, metal helmet, etc.

Cellular phones IC lead frames Electronics, Health care Miniature fasteners Hard disk drives Products of national security and defense, Automobiles, mill dish, bath tub, sink, Cranial plate, Dental plate and other use.

1.6 Organization of the Purpose

- Metal forming technology is growing faster so that many manufacturing products designed and manufactured in a different methods way. One of this techniques incremental sheet metal forming is the recent technology in which it uses gradual step by step forming technique. It can be used to form many complex shaped products.
- Here in this study proposed that to demonstrate of forming a truncated pyramid shaped object using SPIF. And to check the process capability for the forming pyramidal and cone shaped products.
- The size of the dish truncated pyramid from of square upper side 200mm*200mm and having fillet radius at the corner taking radius of the punch. The thickness of the blank is from 2 mm, radius of the punch ranges from 5 mm to 9 mm, incremental depth 0.6mm to 1.2 mm and rotational speed 0 rad/s to 100 rad/s varied to get different result. The parameters obtained from many trials and from related works.

CHAPTER TWO

Literature Review

2.1 Theoretical Background

Single point incremental forming (SPIF) is a sheet metal forming process that allows manufacturing process which does not require a complex tools like stamping and two point incremental forming and multi point forming process. ISF process depends strongly on the forming tool path which influences greatly the part geometry and sheet thickness distribution. Material failure occur in different regions in the deformed sheet the most likely region exist at the corners and also at inclined wall with stretching effect and the shear effect were critical for the damage for the deformed sheet [4-6]. As the tool moves slowly that means the deformation rate decreases so that the formability can be increased. The deformation that occurs at the starting and ending points of the straight line is biaxial stretching. The deformation that occurs between points that tool is in contact with sheet is plane-strain stretching [7,8].

The sheet metal forming is improved by the action of heat so that the metal can easily deforms since the heat makes the metal more flexible. The deformation mechanisms of SPIF and TPIF were increasing stretching and shear in the perpendicular to the tool direction and shear in the tool direction a significant amount of spring back reduction is achieved by the processes of stress-relief annealing method when compared to the original forming process without the application. Due to the localization of forming different of shapes is obtained without damaging even if it takes longer time [9-11].

Increasing stretching and shear perpendicular to the tool direction account for differences between the sine law and measured wall thickness for SPIF and TPIF. Sheet metal thickness reduction in SPIF is obtained by sine law is close to experimental result [12,13]. In order to get optimized formability in the single point incremental forming process, it is crucial to use process parameters according to the effect on the process it cause. Little friction at the tool and sheet interface helps to improve the formability but excessive friction leads to sheet tiring [8].

2.2 Representation of Single Point Incremental Forming

The blank sheet is clamped in a stationary blank holder which holds the sheet from each sides. And the forming tool having spherical in shape having was attached to the spindle of the mill. Fig.2.1 shows the physical set up for SPIF system the punching tool, blank sheet, and blank holding device. The contour for the tool path forms the desired geometry controlled by 3 axis regular CNC milling machine [14].

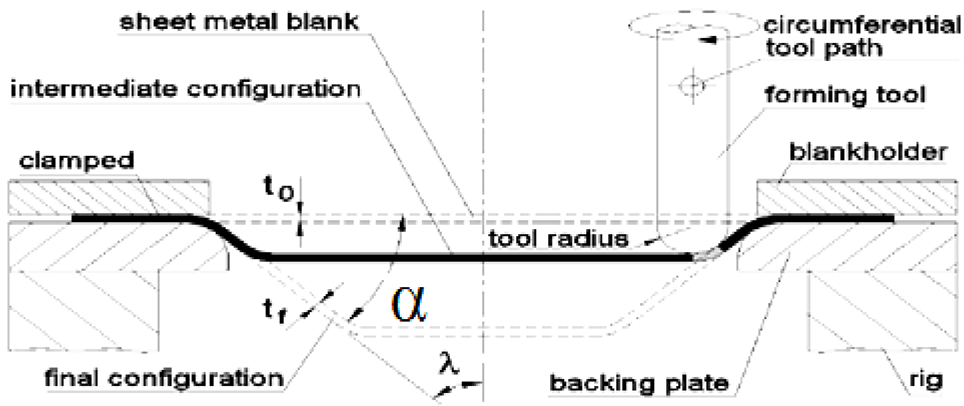


Figure 2. 1 Schematic Represent of a cross section view of SPIF

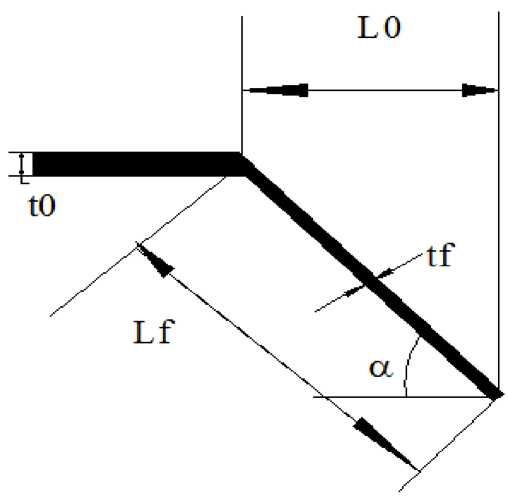


Figure 2. 2 Schematic Represent sheet thickness reduction from the original thickness with respect to wall angle

Incremental Sheet Forming investigated that the thinning in ISF depends on the wall angle, α and is given by the sine law as shown in equation 3 developed from the equation of principle of metal forming in equation 1[12] [15,16].

From the Fig. 2.2 the sheet metal deformed the thickness reduced from T_0 to T_f and the original length l_0 increased to l_f. From theory of metal forming in equation 1volume constant in the metal forming phenomena throughout processes of metal forming. Assume the width is not changed keep constant [12][17].

$$V_o=V_f \text{ ……………………………………..(1)}$$

$$T_o \times l_o \times w = T_f \times l_f \times w$$

$l_o= l_f \times$ **sin**(90-α) reducing *the above* equation ………………………………(2)

Inserting equation (2) and into equation (1) and simplifying, we get the equation (3) below [12]

$$T_f = T_o \sin(90° - \alpha) \text{ …………………………………………………… (3)}$$

2.3 Flow Properties

A more accurate material behavior model for simulation since they either take into account the elastic and plastic strains separately or provide a more rational mathematical basis of hardening function. Some of them can't be directly implemented finite element modeling the material behavior and an expression of Swift equation, that it is indicated in Equation 4, was finally adopted to elastic and plastic strains and to try to achieve a more accurate correlation. Swift expression has been considered by using the averages of the stress–strain curves obtained by tensile tests at various orientations with respect to the rolling direction The plastic part of sheet metals is obtained by tensile test and the flow stress has been approximated by means of the following Swift-type hardening law expressed below in equation 4. Where ε_o true strain for yield stress, ε^p is the effective accumulated plastic strain n strain hardening and k stiffness constant, the result is obtained through universal tensile test. the swift law used to determine the to express plasticity flow property of the aluminum (1050) [18-21].

$$\sigma_y = K(\varepsilon_o + \varepsilon^p)^n \text{ ……………………………………………………………………(4)}$$

2.4 CNC Manufacturing Process

A part program is written, using G and M codes it describes the sequence of operations that the machine must perform in order to manufacture the component. This program can be generated off-line, i.e, away from the machine, either manually or with the aid of a CAD CAM system.

The part program is loaded into the machines computer, called the controller. At this stage, the program can still be edited or simulated using the machine controller keypad/input device.

The machine controller processes the part program and sends signals to the machine components directing the machine through the required sequence of operations necessary to manufacture the component [22].

The application of CNC to a manual machine allows its operation to become fully automated and Combining this with the use of a part program to enable of the machine to perform under the order of programed G-coding and M coding, it performs the tasks with high degrees of accuracy [22, 23].

ADDRESSES -

N refers to the block number.

G refers to the G code (Preparatory function).

X refers to the absolute/incremental distance travelled by the slide tool in the X axis direction.

Y refers to the absolute/incremental distance travelled by the slide tool in the Y axis direction.

Z refers to the absolute/incremental distance travelled by the slide tool in the Z axis direction.

F refers to the feed rate.

M refers to the M code (Miscellaneous function).

S refers to the spindle speed.

T refers to the tooling management.

Each block, or program line, contains addresses which appear in this order:

N, G, X, Y, Z, F, M, S, T;

This order should be maintained throughout every block in the program, although individual blocks may not necessarily contain all addresses [22].

2.5 Tool Path Generation

Tool path generation has direct impact on the dimensional accuracy, surface finish, formability, thickness variation and processing time. The parts formed by spiral tool path have a more uniform thickness distribution as compared to those formed by conventional contour tool path.

Contour milling tool path is a finishing pass, typically defined by fixed Δz increments between consecutive discrete contours. This is also the most common technique used. The disadvantage is it leaves marks at the transition point between layers and creates force peaks. Surface quality depends on tool radius; step size and slope angle as well as lubrication system and rotational spindle speed [1].

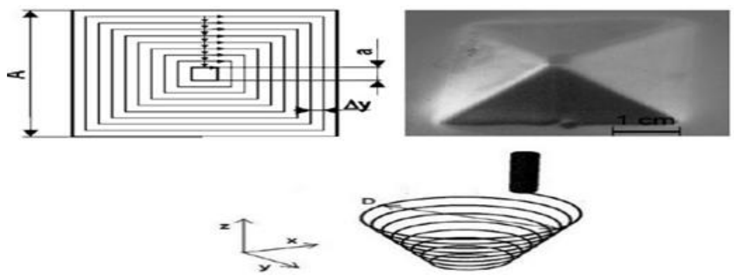


Figure 2. 3 Observed tool trajectories and a formed feature during the experiment

A spiraling tool path was continuous with incremental the tool over the sheet metal complete contour as the tool moves along many sequential contours of the part. Multiple tool path strategies as shown in Fig. 2.3 creating intermediate forms that are defined within the cavity of the final surface and are typically characterized by limited slope angles and curvature [1].

The part is first sliced into a number of layers. For each layer, next, the contour of the part is found. Then, the punch path is generated based on the geometry of the contour. This can be done using commercial software, such as Master CAM. Finally, the punch paths for different layers are stitched to form the complete punch path. Fig. 2.4 shows the flow diagram for defining tool path generation from deciding the dimensions of the contour, generate 3D model, define the stock size, define cutter path, defining machining parameters, deciding the starting and ending point, machining simulation and generate part programming code. The tool path generation method was to compute a sequence of cutter location points from the design surface. Tool path generation methods are classified as (cutter contact) CC-based method and (cutter location) CL-based method depending on the type of tool path generation surface [24].

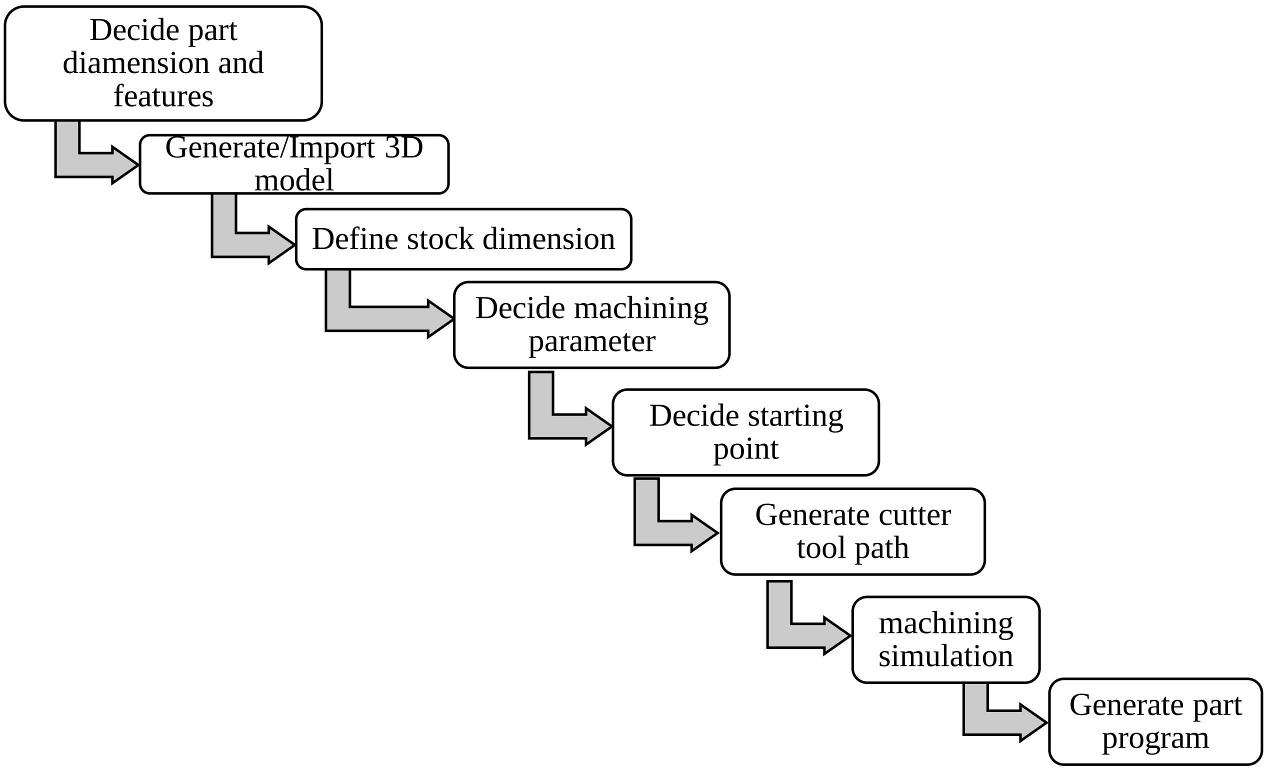


Figure 2. 4 Flow chart for counter tool path generations

2.5.1 Tool Path Strategies for Incremental Forming

Tool path has significant effect on dimensional accuracy, surface roughness, processing time and thickness variation. Thus tool path generation is an important step in incremental sheet forming (ISF). Three different methods have been used to generate the tool path for ISF in the literature (i) tool path generation using commercial computer aided manufacturing (CAM) software's, (ii) Cutter location (CL) based approach, and (iii) cutter contact (CC) based approach. Commercial CAM packages offer different tool path for the machining application. One tool path among them suitable for ISF application is the profile tool path. In profile tool path, tool moves in one plane till it reaches to its initial point. Thereafter it moves vertically downward direction by specified step depth. After reaching to next plane tool continues its motion in the same direction as that of earlier cycle. This process continues till the complete geometry is formed. Profile tool path can produce any complex geometry but it produces a scarring on the surface of the part. This scarring may not be permitted on parts which are aesthetically important. Fig. 2.5 below shows numerical simulation of incremental forming processes [25].

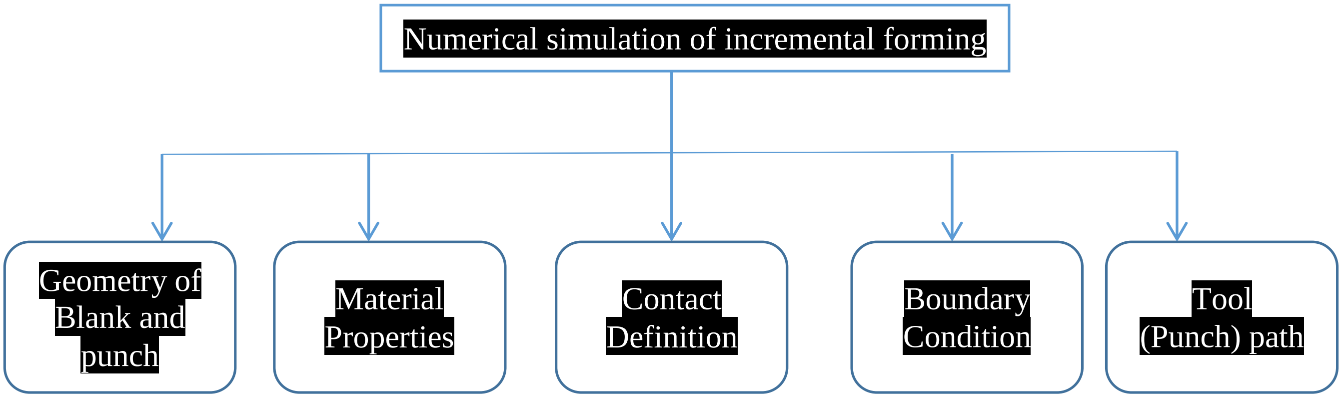


Figure 2. 5 Flow chart for counter tool path generations steps in finite element simulation of forming process

The part program generated using CAM package cannot be given as input for tool path in numerical simulation software's. While the movement is encoded manual step by step sequentially. A typical CNC part program is shown in Fig. 2.6 it includes the G codes for the tool path [25].

```
G0 X0 Y0 Z10
G1 X-51.157 Y-28.244
G1 Z-5
G3 X-47.926 Y-32.052 R52.7673
G1 X-47.926 Y-32.052 Z-5
G3 X-45.438 Y-34.554 R55.0228
```

Figure 2. 6 A typical CNC part program

In the bi-directional tool path, the tool completes a cycle and a quarter of tool path cycle is added before it moves to next cycle. By doing this the position of tool change from one cycle to another cycle change and scar mark is not be visible on the part geometry. Moreover by doing this forming force distributes uniformly along the edge of the geometry and enhances the geometric accuracy of the part shown in Fig. 2.7.This tool path minimizes the twist and enhances the geometric accuracy of the formed component. However it may not be possible to divert the scar mark to unimportant area in all cases. It was also proposed Bi-directional profile tool path with distributed increment, which is not in commercial CAM packages [25].

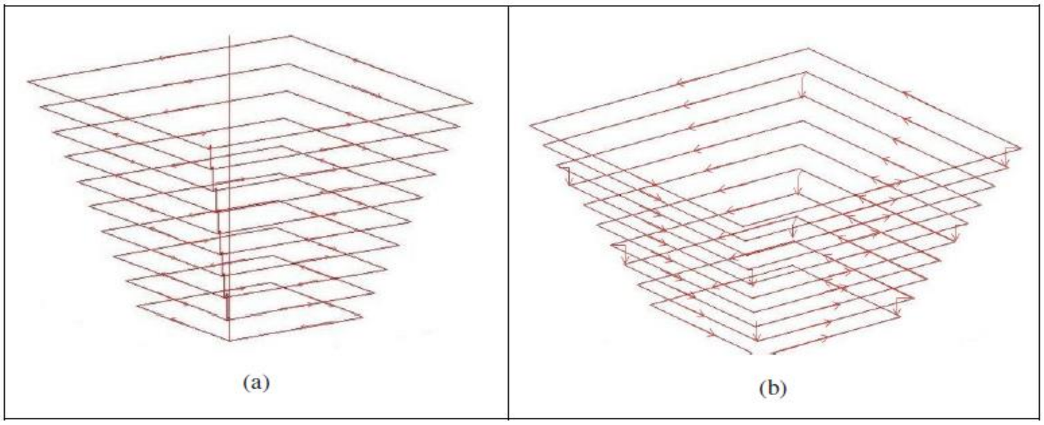


Figure 2. 7 (a) Bi-directional tool path; (b) Bi-directional tool path with distributed increment

2.6 Effect of Process Parameters Affecting SPIF

The SPIF processes of the truncated cone were performed with different tool diameters, wall angles and incremental depth were performed and sheet thickness. It can be found that the incremental depth has greater impact on the plastic zone. The tool's diameter has less impact on the plastic zone and with the tool's diameter increasing the zone expands a little [27,28].

The bigger plastic deformation zone means there are more metal to be formed at one time. So the deformation energy increases and the forming force is bigger. From the relation in equation 2 the wall angle α has large effect on the sheet thinning and the original sheet thickness also determinant parameter on sheet thickness reduction. In addition other parameters like spindle rotational speed and feed rate also have effect on SPIF [26-30].

2.6.1 Minimum Thickness

The final thickness of a part formed by SPIF can be estimated using the sine-law. This law was originally developed for the shear forming process. Where t_0 is the initial thickness, t_f the final thickness, and α-the wall-angle measured with Respect to the horizontal [12, 13][27].

The reduction rate of thickness is of great concern in manufacturing industry. However, thickness reduction is one of the main defects of incremental forming, especially for parts with a steep wall angle. As the incremental forming is highly dependent on the tool trajectory and on the minimum thickness was [31].

2.6.2 Forming Angle

Forming angle is the angle between the trend of the tool motion (or tool path) and the x-y plane of the initial flat sheet. This angle is strictly related to the material and the sheet thickness. Maximum forming angle is a parameter specific for each material which is the angle that a material can be drawn before any failure occurs. In which t is the thickness of the sheet at the limit of formability, εt is the thickness strain. The formability is expressed as the maximum forming angle, αmax that a sheet would endure without fracturing [32-34].

2.6.3 Influence of the Vertical Step Size

The second most influential parameter in SPIF of the product is the increment of the vertical step of the forming tool. Taking various vertical step sizes Δz of 0.1, to 3 mm were used for determining the impact of the vertical movement on accordingly the strain and stress values get various results [35-37].

2.6.4 Influence of Spindle Speed

Spindle speed has significant influence on SPIF process like other parameters in single point forming process. Higher forming speeds leads to higher formability due to increase in heat generating and rise in temperature which simplifies the forming process. But there are some defects that can be emerged by increasing the forming speed due to very high rotational speed create local deformation on every point it contact with sheet metal which leads crack [38].

2.6. 5 Influence of Tool Diameter

A greater deformation of sheet metal is possible in SPIF Small tool size is preferred to get the required shape at a faster rate, but the possibilities of failure due to localized stress are bigger [39].

2.7 Forming Forces

As expected, smaller forming forces are required at1000 rpm. In both cases, the vertical force F_z predominates over F along X and Y direction in each stages of the forming process The wall deform faster than the flat part, giving rise to a failure by excessive stretching of the wall. Apart from the physical explanation, what it is really important is that the appearance of this maximum in the forces occurs well in advance of the final failure. Due to the presence of spring back effect on the sheet tool was still in contact with the work piece (resulted in the measured force) due to the spring back of the sheet metal [40, 41].

Experiments were conducted to measure the forces generated during forming of a pyramid. Except the step size of 0.635 mm, the work piece material (0.8 mm, Al 5052), the tool (6.35 mm radius), and the forming conditions (45 degree wall angle) were the same as those used in the trial runs described above [40].

The steady-state force in the z direction was also constant but much larger, compared to the forces in the x and y directions. The force in X and Y direction is dependent on the tool movement once the tool moves in X direction the load in Y component is lowered to zero. Whereas the force on the tool once it moves in Y direction the load in X component is lowered to zero. The forming force in the z direction was independent of the direction in which the tool was moving. The large peak force corresponded to the downward motion of the tool at the beginning of the new pass. The second force marked was force measured while the tool was moving and forming the sides of the pyramid [40, 42].

An Encastre boundary condition was assigned to the outer region of the sheet metal part to simulate the clamping effect from the fixture. Surface to surface contact was used to describe the interaction between the tool and the sheet. The sheet surface was assigned as the slave surface and the surface of the tool was the master surface. The friction coefficient of 0.1 was used in the simulation. The friction value was formulated using the penalty method and an isotropic directionality was assumed [40].

2.7.1 Analysis of the Forming Process Using Analytical Model

A rough estimation of the state of stress of the blank under deformation can be obtained by analytical models, while more detailed FEM simulations must be performed to go inside the matter and assess the influence of the main process parameters. Referring to the geometrical setting and notation of Fig. 2.8 representing a negative forming, the z axis is taken along the direction of the incremental depth steps, and the y axis along the current motion direction [43].

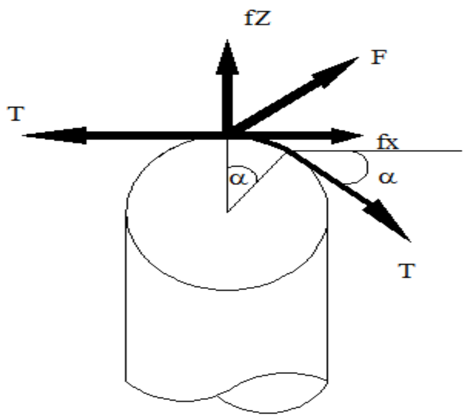


Figure 2. 8 Schematic diagram of force component on metal sheet incremental forming

With reference to Fig. 2.8, the total effort causing material deformation, *F*, can be well approximated being equal and opposite to the resultant of the two traction forces *T* at the borderline of contact surfaces [43].

The tension force *T* on the metal sheet is:

$T = 2 \times l_c \times t_f \times \sigma$ ....(5)

Where Length of the ribbon l_c actual sheet thickness t_f is expressed as a function of the initial thickness t_o and of the deformation ε, it can be obtained: The two Cartesian components of interaction force at the end effector can now be simply expressed by equation 6 [43].

$$\begin{cases} Fx = T(1 - \cos\alpha) \\ FZ = T\sin\alpha \end{cases} \quad \text{……………………………………………………………………..(6)}$$

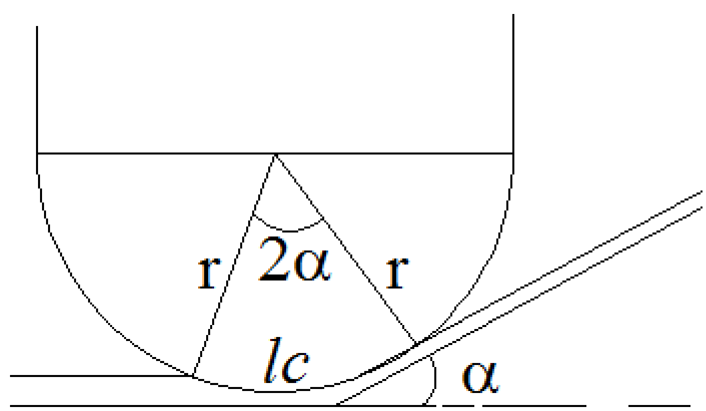


Figure 2. 9 The interaction between sheet and the tool

The chord length in Fig. 2.9 is calculated from the circumference circle of the tool that is 2πr for full 360° taking the angle that can be made by two contact point of the sheet and the tool. The cord length computed in equation 7 depends on contact angle and radius of the tool. The angle it makes 90^o between the tool radius and the sheet in contact [44].

$$l_c = \frac{\pi r \alpha}{90} \quad \text{.........(7)}$$

2.8 Experimental Studies on SPIF

Reported experiments in brass sheet 70/30 with 0.5 mm thickness were developed with the aim of provide relevant information for prototyping and customization of products made of this raw material, such as locks mirrors. Experiments were performed aiming at mainly set the wall angle (α) to sheet brass 70/30 with 0.5 mm thickness, altering step vertical (Δz) and machining strategy. The model of study was based on a truncated pyramid with a square base of side 220 mm, depth 40 mm and radius of concordance holds the size of the tool. For the project of this blank was using Solid Works Software. For machining strategies Edge CAM® software was similar with that of Master Cam used to show the simulation for tool movement [45].

2.9 FEM Simulation Studies on SPIF Using ABAQUS Modules

ABAQUS/CAE is a complete ABAQUS environment that provides a simple, consistent interface for creating, submitting, monitoring, and evaluating results from ABAQUS/Standard and ABAQUS/Explicit simulations. ABAQUS/CAE is divided into modules, where each module defines a logical aspect of the modeling process; for example, defining the geometry part module, defining material properties module, step module for sequential loading, interaction module, load module assembly module and generating a mesh. As you move from module to module, you build the model from which ABAQUS/CAE generates an input file that you submit to the ABAQUS/Standard or ABAQUS/Explicit analysis product. The analysis product performs the analysis, sends information to ABAQUS/CAE to allow you to monitor the progress of the job, and generates an output database and some of the module discussed below [46].

2.9.1 Step Module

Step module allows you to define boundary conditions, predefined fields, and interactions The Nlgeom setting for a step determines whether ABAQUS account for geometric nonlinearity in that step. The Nlgeom setting is turned on by default for ABAQUS/Explicit steps.General procedure containing an ABAQUS/Standard self-contact interaction, a pressure load, and an inertia relief load with a Dynamic, Explicit procedure used [46].

2.9.2 Mesh Module

ABAQUS/Explicit for three dimensional solid is meshed are topologically equivalent to these shapes S4R are used for stress analysis, because the geometrical property of the mesh is not affected. Typically, shell elements assume a plane stress state and have small thickness compared to its length and width [47, 48].

2.9.3 Load Module

2.9.3.1 Boundary Conditions

Modeling the interaction between the tool and the sheet is one of the most important considerations necessary to simulate the incremental forming process correctly. Using this BC we allow the tool path along X, Y and Z directions. So the rigged tool allowed to deform the sheet along its path [33]. The sheet blank is experimentally supported on a four-sided fixture and is clamped rigidly. From numerical point of view, the sides of the initial blank are fixed in all directions and for each simulation; a uniform temperature has been applied to the entire sheet [49]. ENCASTRE Fully built-in (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0) the movement along X, Y and Z direction is constrained and the rotation along X, Y and Z is also constrained [46].

2.9.4 Interaction Module

The contact conditions were implemented using surface to surface elements with asymmetric contact, being sheet and tool respectively the master and the slave component. Columbian friction with a friction coefficient equal to 0.1 was adopted, this value is commonly assumed in well lubricated sheet forming [50]. The developed model also suggests that smaller friction results in lower stress, which potentially increases the SPIF formability [51].

2.10 Explicit/ Implicit

The differences between two methods were discussed earlier. Because of the nature of the process which is incremental, if the software is able to pick smaller increments it can greatly affect the accuracy of the results. One of the main differences of the two methods picking and organization of these increments which in the implicit method it is very time consuming. The explicit method was chosen to simulate the processes, not only to save time in calculating incrimination time that has a big deal, but also to improve the accuracy of the whole process. Fig. 2.10 show the assembly for single point incremental forming of the sheet blank and the punch in addition the ENCASTRE condition for the sheet that means the sheet is fully built-in all sides of the sheet blank [52].

The FEM model of asymmetric incremental sheet metal forming consists of 3D rigid objects (the rod shaped forming tool and the upper and lower blank holder plate) and a deformable blank of the analyzed material. The stress-strain curve was approximated by the Hollomon potential law. [47].

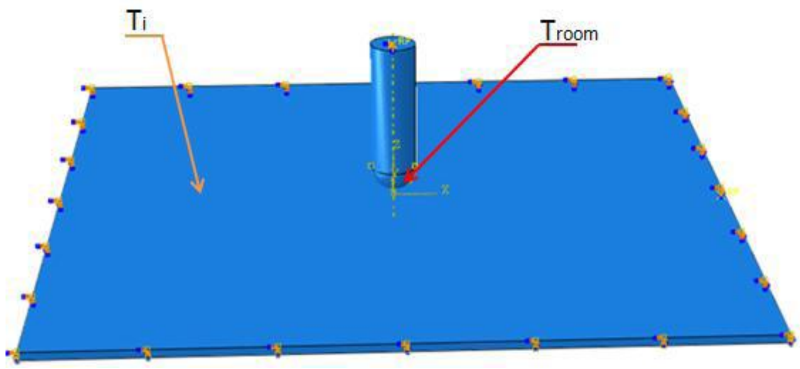


Figure 2. 10 Three-dimensional exploded view of numerical model used in SPIF

The sheet blank is experimentally supported on a four-sided fixture and is clamped rigidly to this fixture with a backing plate to support the punch displacement. From numerical point of view, the sides of the initial blank are fixed in all directions and for each simulation; a uniform temperature has been applied to the entire sheet [49].

In the present work, ABAQUS (6.14) software code was used for the numerical simulation of SPIF process to fabricate conical cups. The material was AA2024 alloy. The sheet and tool geometry were modeled as deformable and analytical rigid bodies, respectively, using ABAQUS. They were assembled as frictional contact bodies. The boundary conditions for tool were x, y, z linear movements and rotation about the axis of tool. True stress-true strain experimental data were loaded in the tabular form as material properties [53].

For the pyramidal cups, the maximum equivalent stress induced is 269 MPa. The maximum equivalent stress was found at the corner edges formed by the side walls of the cups. The shear stress was due to compressive stresses in the blank sheet. The equivalent strain was found to be 2.026 after completing the job or analysis is shown in Fig. 2.11 for the pyramidal cup [54]. Since maximum stress in the result less than ultimate stress of aluminum 2024 which is345 MPa [55].

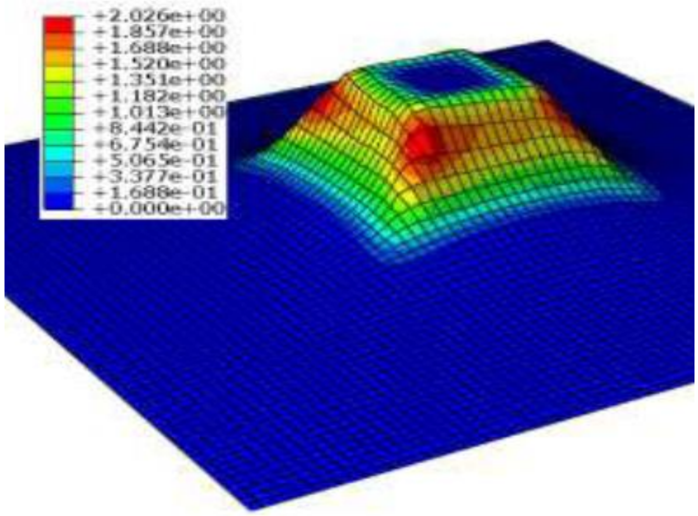
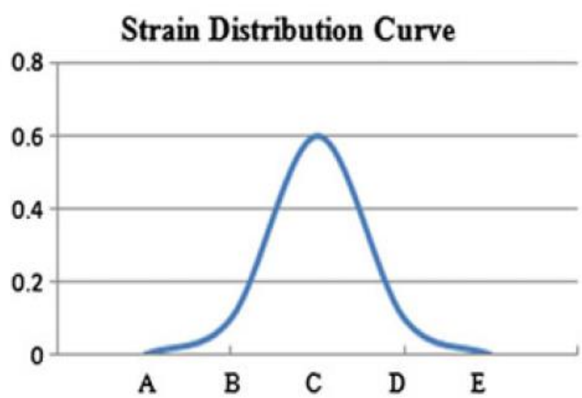


Figure 2. 11 Equivalent strain induced in a pyramidal cup

2.11 Stress Evolution and Strain Distribution

In SPIF there are frequent load unloading effects due to this the part gets work hardened it requires more stress to be deformed. In order to compare the stress levels it is important to note that due to work hardening of the material the last stage is the most significant stage of the process. All the failures occur in that stage and the material is in the highest work hardened level. The sheet failure start as the stress level get higher than ultimate stress [56].

Investigate the strain distribution in the deformed product of aluminum sheet shown in Fig. 2.12 a), the strain distribution is maximum at the center. For the analysis of strain distribution in the sheet deformed by ISF process for the formed material, is shown in Fig. 2.12 b) were identified on the deformed sheet [3].



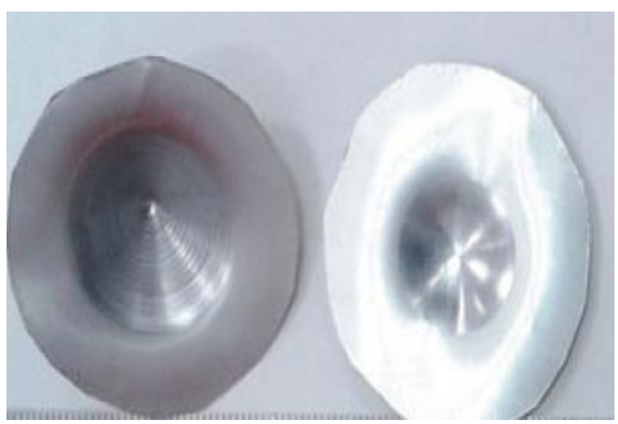


Figure 2. 12 Strain distribution for the formed cone (a) and the formed cone (b)

2.12 Stress Invariants

Constitutive models in ABAQUS formulated in terms stress invariants. These invariants defined as equivalent pressure stress,

$P = -\frac{1}{3}\times(\sigma_1 + \sigma_2 + \sigma_3)$ ……………………………………………………………….………(8)

The Misses equivalent stress,

$\sigma_{equivalent}$ = Equivalent stress, $\sigma^2_{\varepsilon} = (\sigma_1 - \sigma_2)^2 + (\sigma 2 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2$ [46]

Maximum shear stress theory – Tresca principle

Max.{ $\left|\frac{\sigma 1-\sigma 2}{2}\right|, \left|\frac{\sigma 2-\sigma 3}{2}\right|, \left|\frac{\sigma 3-\sigma 1}{2}\right|$}…………………………………………………………………..(9)

$\varepsilon_v = \frac{1-2\nu}{E}(\sigma_1 + \sigma_2 + \sigma_3)$ …………………………………………………………………(10)

Equivalent stress, $\sigma^2_{\varepsilon} = (\sigma_1 - \sigma_2)^2 + (\sigma 2 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2$ ……………………………… (11)

The maximum normal strain failure criterion specifies a limiting value of the principal strains.

Failure occurs at a point in a body when the maximum strain at that point exceeds the value in a uniaxial test of the material at yield point

Maximum of this the three strain values (ε_1, ε_2 & ε_3) should be less than ε_y unless the material failure occur [57].

CHAPTER THREE

Materials and Methodology

First the model for truncated pyramid is prepared according to its dimension mentioned CAD software **solid work** graphics in 3D and 2D**,** this model further analyzed to determine tool path generated by using **Master CAM X5** and also it can generate a code that have a command to the tool path in 3-axis milling machine. The generated code exported in to CNC milling machine so that the activities for the cutter is guided by the M and G coding.

The formability of the sheet metal checked by using design software **ABAQUS** to do the simulation for the formation sheet the stress-stain relationship in a single point incremental forming.

3.1 Methodology Procedure

Arrange the domain of the experiment that is the parameters needed like initial thickness of sheet metal & properties of the sheet metal including density of blank, elastic modules, plasticity relation. Size of the specimen and the product measured in a metric measure X, Y & Z

The variation of parameters which affect the result of SPIF is discussed in of them are:

- Determine optimum rotational speed of the tool that spindle in CNC milling machine makes rotation.
- Calculate the maximum Incremental Depth in each step that the tool can make.
- The radius of the tool used in single point forming process.
- The starting point for the tool distance or gap of with respect fixture

Fig. 3.1 shows the flow diagram for metal forming on sheet using SPIF from the start that is creating the geometry to final result obtained for optimum parameters for the single point incremental metal forming processes.

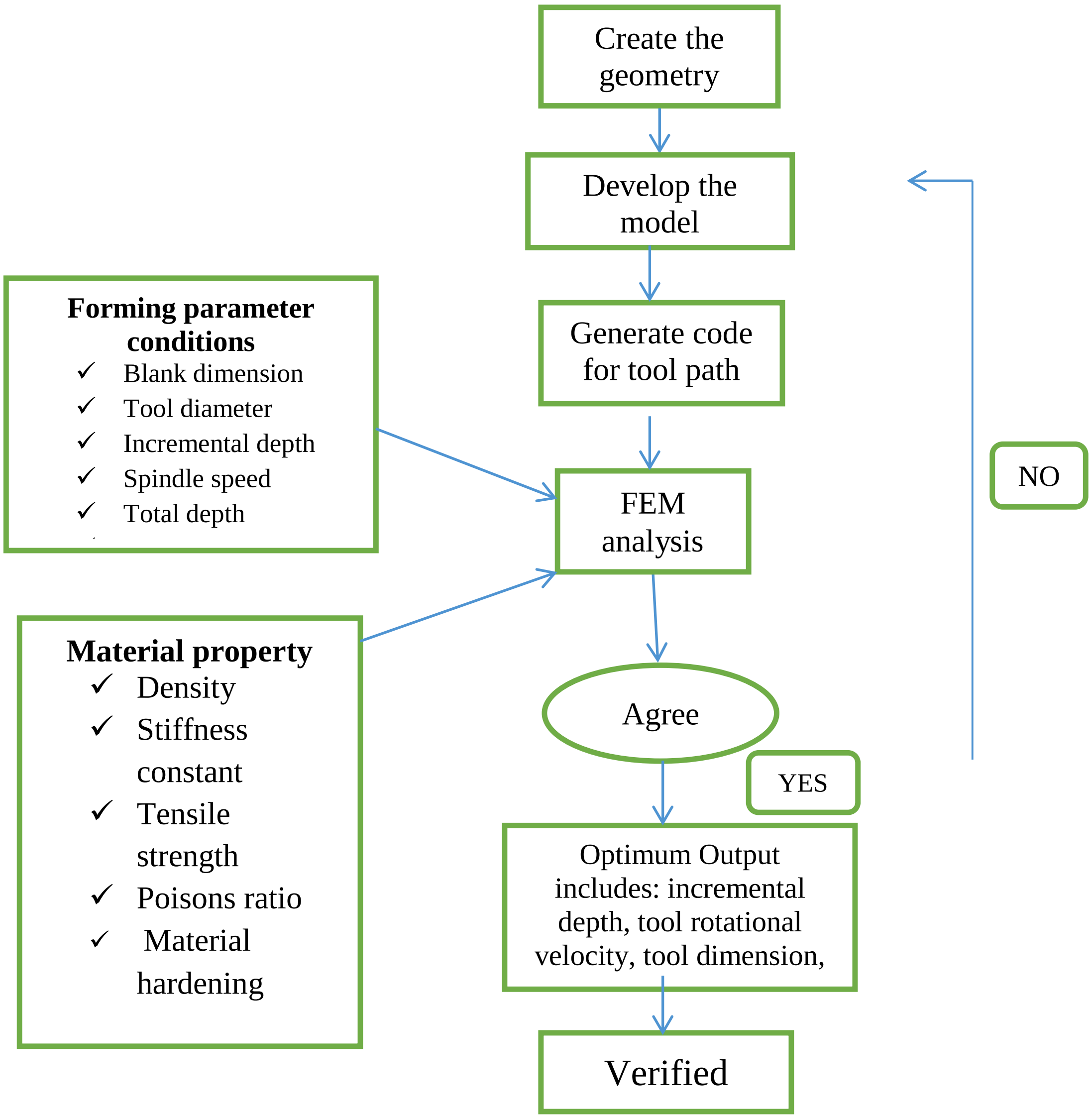


Figure 3. 1 Processes flow diagram

3.2 ABAQUS Modeling Approaches and Simulation Techniques

The most efficient way to analyze this type of problem is to analyze the forming step using ABAQUS /Explicit.

In the results presented here, the drawing process is simulated by moving the reference node for the punch downward with incremental depth from 0.6mm to 1.2mm for 1second.

3.2.1 Geometry of the Blank and the Punch

The blank is initially square, 200 mm by 200 mm, and have the 1.5 mm thickness. The rigid die is a spherical shaped with a 5mm, 8mm and 9 mm radius. The blank is deformable sheet made of aluminum and the punch is discrete rigid made of tool steel is shown in Fig. 3.2 a & b.

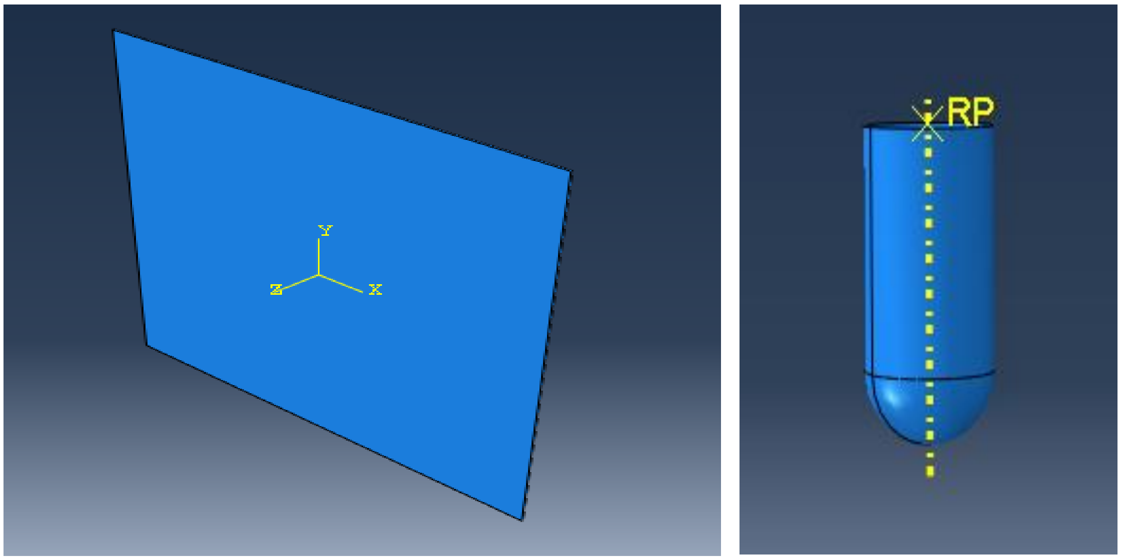


Figure 3. 2 shows sheet blank made by ABAQUS (a) and shows punching tool (b)

3.2.2 Process Set Up ABAQUS/Explicit

Comparing results from an analysis sequence that uses ABAQUS/Explicit for a forming and compare characteristics of different results of stress and strain.

This illustrates the forming of a three-dimensional shape by a single point incremental forming. In general, the forming procedure involves a forming step from the initial press the sheet by the tool until it complete the desired shape. The goal of analyzing the forming procedure is to determine the final deformed shape.

3.2.3 Load Module and Boundary Conditions

The first boundary condition is ENCASTRE Fully built-in (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0). Fig. 3.3a show that the sheet tied at the four sides of the sheet by the blank holding device so that edge of the sheet is not allowed to translate with respect to the blank holding device.

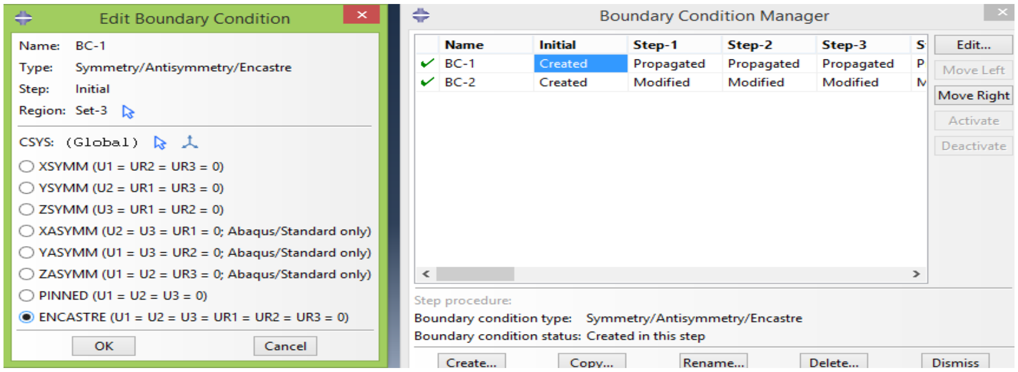


Figure 3. 3 Boundary Condition 1 for ENCATRE condition (a) and boundary condition 2

The Second boundary condition BC-2 indicated in Fig. 3.3b shows the geometry for rectangular contours, so that the dimensions directs the path of the tool. Therefore punch can move in x-direction, y-direction, z-direction, according to the predefined dimension and also can rotate with respect to z-axis.The dimension is in SI unit system U3=-0.0012m which means the incremental depth is 1.2mm and UR3=10 radians and the time scale factor is 0.2 second there for the tool rotates in 50rad/s which is equal to 477.46 rev/min.

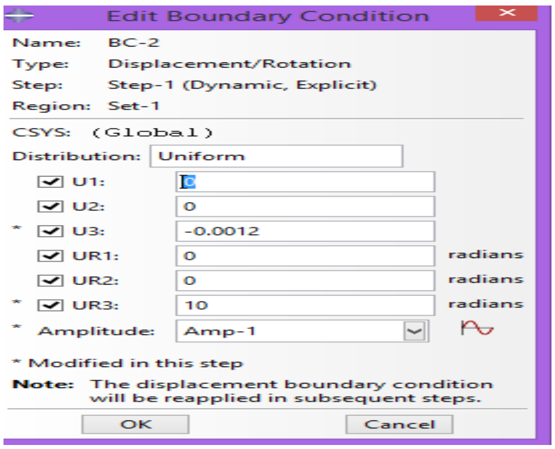


Figure 3. 4 Boundary Condition two for tool movement

Similar with the dimension in boundary condition two is the force applied to the punching tool in the tool reference point. Reference point (R.F) is the center of symmetrical punching tool. The punching tool directly first pushes the sheet in downward in perpendicular to the sheet so that force deforms the sheet create an indentation. Then the tool moves on the sheet in X and Y direction with respect to boundary condition 1 as we from the above Fig. 3.4. Repeating successively the tool make deform the blank in with respect to the path of the tool until it gets desired shape during forming.

The loading condition computed with respect to the sheet thickness, chording length and wall angle

$T = 2 \times l_c \times t_f \times \sigma$

$l_c = \frac{\pi r \theta}{90}$

Where ε_o is true yield strain value 0.00142 and ε^p is plastic strain value is obtained from stress-strain relation swift low. We used average of the of the tension value since the plastic strain value ranges from zero to ultimate strain value.

The value for force along Z & X this way, once the load on the tool indent and moves to X direction here the load in Y is zero $FZ = T\sin\alpha$ and $Fx = T(1 - \cos\alpha)$

The blank is held in all four sides and the punch applying a concentrated load of at the reference point of the punch. The reference point is the center point of the punch at top of the center of the circular punch. Further loading on the blank is applied by contact forces with the punch through all steps of forming. The loading as shown in Fig 3.5 begins by the punch strike with the given incremental depth on the sheet with the magnitude of negative 1250 N in step one, this can be the maximum loading needed in the forming.

Then after the tool move XY plane with respect to the dimension of the rectangular geometry the loading condition accordingly. In step two the punch tool with the concentrated load moves two the negative X-direction, we consider the Y -component force is zero, the force in Z direction is negative 1250 N and the load in X direction is negative 750 N. Then after the punch tool moves two negative Y-direction the load here in Y-direction is negative 750 N. Likewise the loading continues to positive X direction and X direction the loading is positive 750 N along and then it continues next step with 750 along positive X and the Z component is still negative 1250N.

After completing the first rectangle the tool prepares for the next rectangular contour. It strikes again on the corner point of the second rectangular contour with the given incremental depth so that the sequence continues until it completes all the rectangular contour.

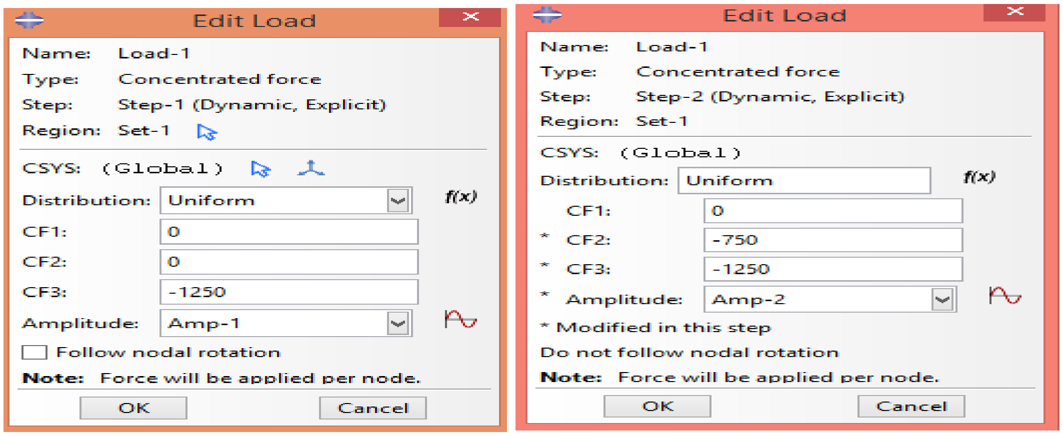


Figure 3. 5 a) the concentrated load applied in step 1 (b) the loading condition in step two

3.2.4 Interactions Modules

Contact interaction is considered between the blank and the punch with a penalty friction condition with coefficient of 0.1 is shown in Fig. 3.6a Surface to surface contact explicit type which has the master surface is the surface of the punch instance which is spherical m-surf 1 region and slave surface is the sheet blank part s-surf-1 region shown in Fig. 3.6b. The assignation is based on the master surface should be rigid part and the slave region is the deformable part. Unlike the sheet metal the punch has translational and rotational degrees of freedom along x, y and z direction and rotation along z axis.

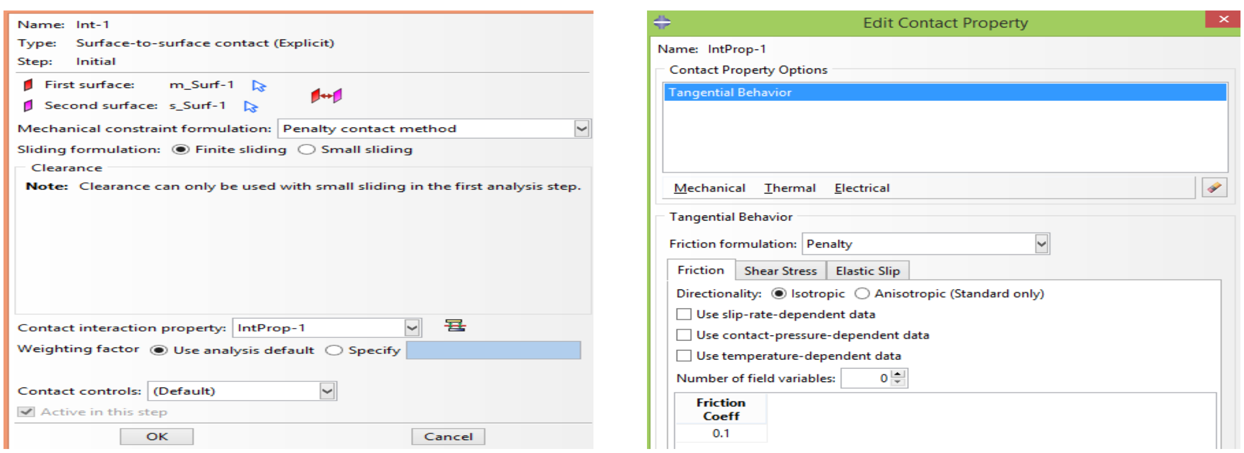


Figure 3. 6shows contact property (a) and surface to surface between the master and slave surface(b)

3.2.5 Mesh Modules Design

The blank is modeled with C3D8R: An 8-node linear brick, reduced integration, hourglass control. C3D8R; while the punch modelled three-dimensional rigid surface elements (R3D4).

The mesh designed for sheet in the experiment is 0.0067 approximate global size is used is shown in Fig. 3.7 a & b the mesh the sheet instant and the punch. The blank is aluminum sheet) that is deformable three dimensional eight node elements and the punch is steel (1040) rigid surface meshed with three dimensional rigid surface element (R3D4). Under the forming process the tool exist in the elastic region the deformation is reversible for large stress it face. The number of mesh element in mesh design for aluminum blank sheet is 2025 elements and for the tool 297 elements.

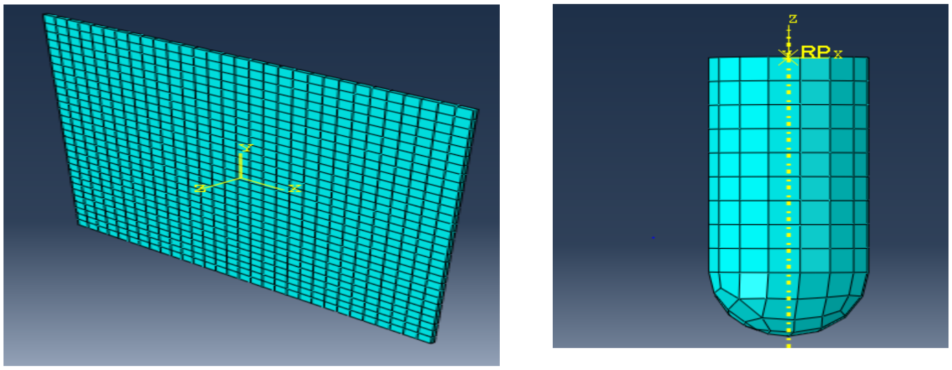


Figure 3. 7 shows Abacus mesh model for the sheet metal (a) and the punch (b)

3.2.6 Steps Modules

Using ABAQUS/Explicit for the forming procedure involves a single forming step where the rigid punch is pushed against the blank by applying a concentrated load. While the blank is held by the blank holder.

First step: the punch is brought in contact with the blank by applying a small displacement to the reference point applying a concentrated load. The small advancement by the tool creates the sheet deformed by small change in the sheet. A concentrated load is applied to the reference point of the punch. Second step: a concentrated load is applied to the reference point of the punch to the blank in the negative y-direction keep the x-component constant. Third step: then the punch moves negative x-direction keeping y-direction constant a concentrated load is applied to the reference point of the punch to the blank.

Fourth step: then the punch moves positive y-direction keeping x-direction constant a concentrated load is applied to the reference point of the punch to the blank. Fifth step: then the punch moves positive x-direction keeping y-direction constant a concentrated load is applied to the reference point of the punch to the blank. Sixth step: then the punch moves negative x-direction and negative y-direction a concentrated load is applied to the reference point of the punch to the blank. After this complete movement for single rectangular contour the rest of the steps go like this by only change in the dimensions of the rectangle.

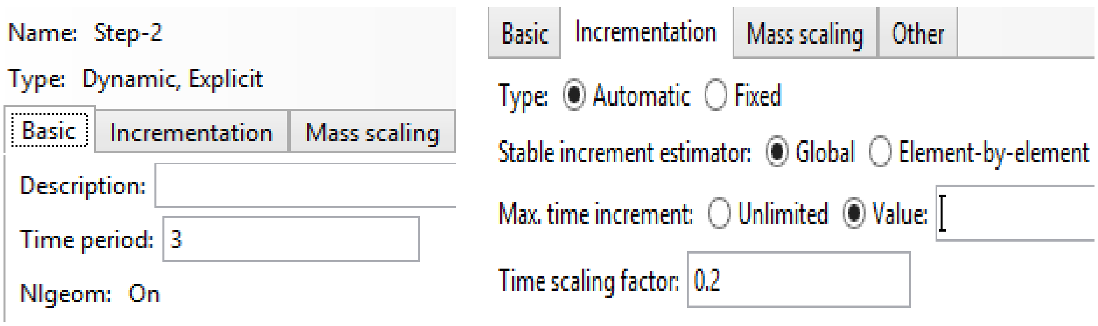


Figure 3. 8 Step -2 three second and with nonlinear geomtry (a) and time scale factor is 0.2 (b)

To complete the forming operation we need to continue the steps until step 30.In step there is there is the filed output is the parameter we need is selected from the drop down menu found in the field out request box shown in. The output request we ask is that von miss stress result, plastic strain and equivalent strain value to the whole model the output result is evenly spaced with time interval for every step. Fig 3.8a) shows the step module uses 3 second for step module and based on nonlinear geometry that means deformation is large. The time scale factor vary in the scale factor applied to a particular deformation. For time scale 0.2 the rate change in time is 0.2second in.

3.2.7 Analysis Types

As described earlier, the import capability in ABAQUS is utilized to run the forming steps as an explicit dynamic analysis. The result of the steps is shown in the Fig. 3.9 from initial unreformed blank sheet till final deformed output product.

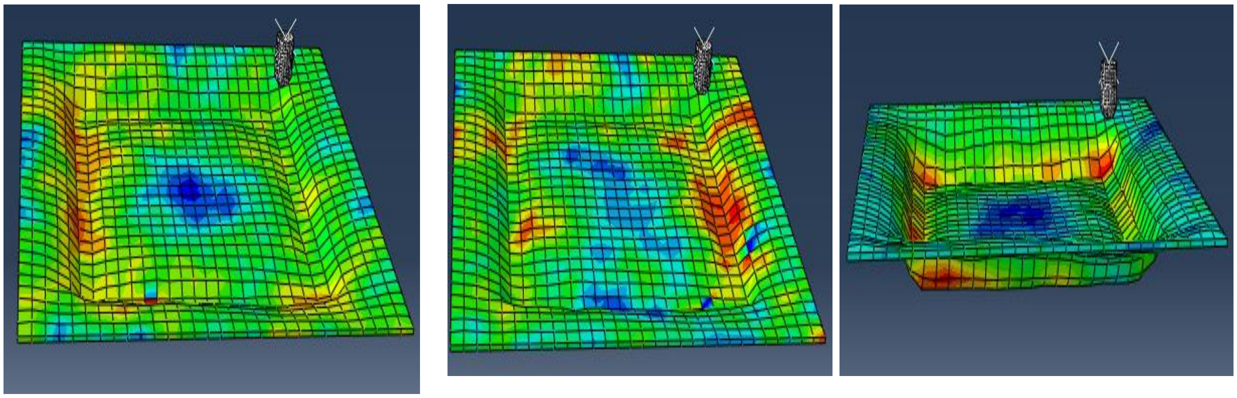


Figure 3. 9 sequencial step to create a pyramid from the blank sheet metal

3.3 Experimental Set Up

In our thesis we identified four critical parameters that have effect on single point incremental forming process these are sheet thickness, tool radius, step (incremental) depth and spindle rotational speed is shown in Table 3.1.

And all this parameters have four different levels to vary the value of the magnitude. The finite element modeling of SPIF process was carried out using ABAQUS (6.13) software code to fabricate parts like a cone shaped or pyramidal.

We can perform many tests but for we perform twelve test by combining different parameters as shown in Table 3.2 by maintaining the three parameters constant and varying one parameter we tried see the effect on the result. For the next three parameter the same procedure is followed.

In the Fig. 3.10 a is a exploded model is blank holding fixture for SPIF process it describes the sheet is held by the bottom and upper frame held tight using bolt and nut. In the Fig. 3.10b the frame is again held with the slot in the milling firmly to avoid vibration while forming. Here the tool is fixed stationary and the table moves along X, Y and Z directions.

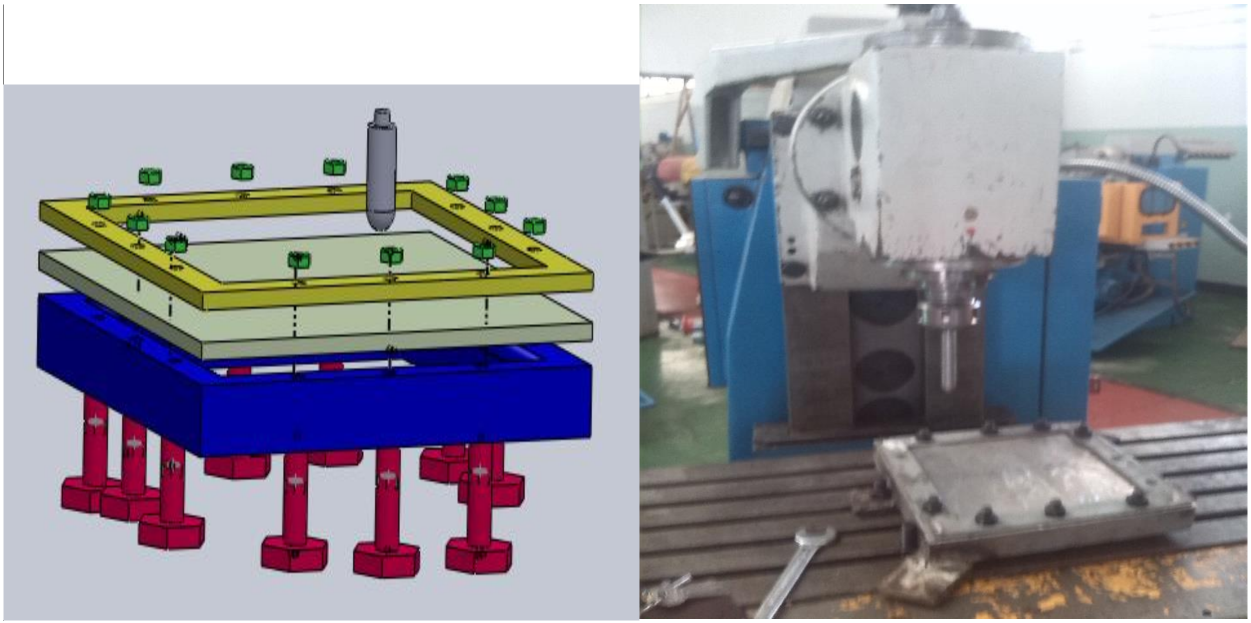


Figure 3. 10 exploded model for complete set up for SPIF (a) and practical assembly of sheet and blank holding device with milling slot (b)

The sheet hold by blank holding device in milling machine, once the sheet is tied by bolt and nut so that the sheet stretch and by reducing its thickness. The tool movement was in incrementally, it starts from outside larger one to smaller one taking different rectangle as a contour path for the tool. As the tool reaches the sheet it pushes down ward and then sheet deforms taking the shape of the sheet similar to the contour path of the tool. For each parameters we need three level and their value is obtained from many trials, depending on the effect of the result and some are taken from related works. The level for distance of the tool from the fixture is used only two levels 2.5 cm and 5 cm. using two levels we can describe the effect of the parameter easily from the result.

Table 3. 1 Four process parameters and three levels

Factor	Symbol	Level 1	Level 2	Level 3
Tool radius, mm	R(mm)	5	8	9
Step depth, mm	Δh(mm)	0.6	1	1.2
Tool rotation, rad/s	ω (rad/s)	0	50	100
Distance from center	S(cm)	5	2.5	

Table 3. 2 Controlled parameters for experiment

Treat No.	S	R	Δh	ω
1	1	1	2	1
2	1	2	2	1
3	1	3	2	1
4	1	2	1	1

5	1	2	2	1
6	1	2	3	1
7	1	2	2	1
8	1	2	2	2
9	1	2	2	3
10	1	2	2	1
11	2	2	2	1

3.4 Materials Used

Tool steel for punch to push the sheet, it is considered as rigid body, that does not deform to the loading in the current experiment. The tool steel can be made from high speed steel, carbide steel. The blank used is Aluminum (1050) and punch is Steel their property is described in Table 3.3. The material hardening value for Aluminum is 0.235 and true strain for yield stress is 0.00142. In addition the chemical composition for aluminum (1050) is presented in Table 3.4[58].

The equation for swift law for aluminum describes flow and hardening equation. The data obtain using the equation of swift law for aluminum (1050) $\sigma_y = 119.5(0.00142 + \varepsilon^p)^{0.235}$ and graph Fig.3.11 was drawn from the data.

Table 3. 3 Material properties for the blank sheet and punch tool

Property	Aluminum(AA1050)	Steel
Elastic modulus (GPa)	70	200
Poisson ratio	0.33	0.3
Yield strength (MPa)	20	353
Ultimate stress(MPa)	70	518.8
Stiffens constant (MPa)	119.5	510
Density(kg/m^3)	2.700	7.850
Behavior criterion	Von-misses- plasticity	Von-misses- Elasticity

Table 3. 4 chemical composition of aluminum 1050A (S1B)

Element	AL	Si	Fe	Cu	Mn	Mg	Zn	Ti	Other
Min	99.5								
Max		0.25	0.40	0.05	0.05	0.05	0.07	0.05	0.03

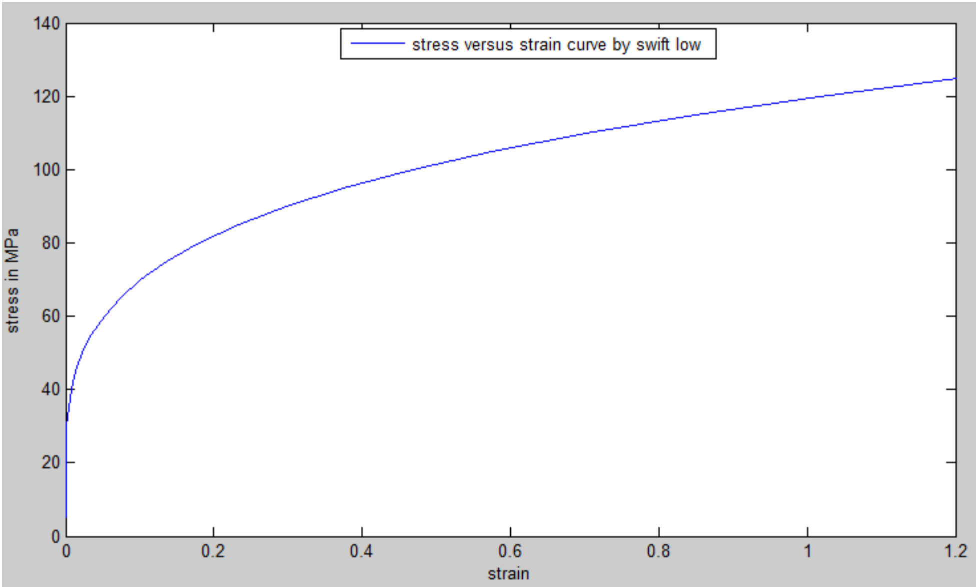


Figure 3. 11 shows the stress strain relationship according to swift law

3.5 Master CAM

Master Cam is professional software is customized to metal cutting operations like CNC lath operation and CNC Milling operation. It is suitable for simulation of cutting operations using tool path and the machining metal cutting operations.

SPIF uses forming operation rather than cutting operations therefore the cutting tool is replaced by forming tool. So that the tool is prepared with spherical or ball shape at the tip of the tool. As the tool moves it deform the sheet taking the sheet the shape of the tool as a generated and the shape of the path directed.

The tool path is formulated simulated using contour tool path, so that different contours of rectangles prepared using extruded cut in increasing depth of cut. Path of the tool is dictated by the rectangular path of the rectangle drawn. The path is follow the rule by G and M code therefor the operation aided by CAD CAM system.

The size of the tool radius changed from to 5mm, 8mm, and 9 mm the tool selection from tool magazine. Due to the tool cylindrical shape it creates fillet at the corner. The tool rotational speed can be varied from 0rad/s, 50rad/s and 100rad/s in parameter set up in addition the incremental depth from 0.3mm, 0.6mm 1mm and 1.2mm.

The size of each rectangle is drawn by taking the data for incremental depth wall angle of the deformed sheet. As the size of rectangle reduce step by step to form a pyramid as the tool increasing depth of cutting since we changed the cutting tool by forming tool.

The tool complete one rectangle and go for the next rectangle accordingly, as is seen from the Fig 3.12 a) that outside to inside fashion that means the tool starts from one corner moves the rectangular path and ends at that point and then it repeat for all contour. The movement of the tool move in the way that from outside and it goes inside. Fig. 3.12 b) shows how the tool removes the metal part incrementally down ward according to contour path. Fig. 3.13 shows side view for moving tools and show the tool increment each steps. The tool path compensation direction is left, that means the tool is in the right side of the path shown in the Fig 3.14 which determines the dimension. For 200mm by 200mm rectangular contour the right side compensation means the net shape is 200mm by 200mm square. In addition tip compensation is tip that means for 1.2mm increment the sheet indent 1.2mm since the sheet is at zero depth.

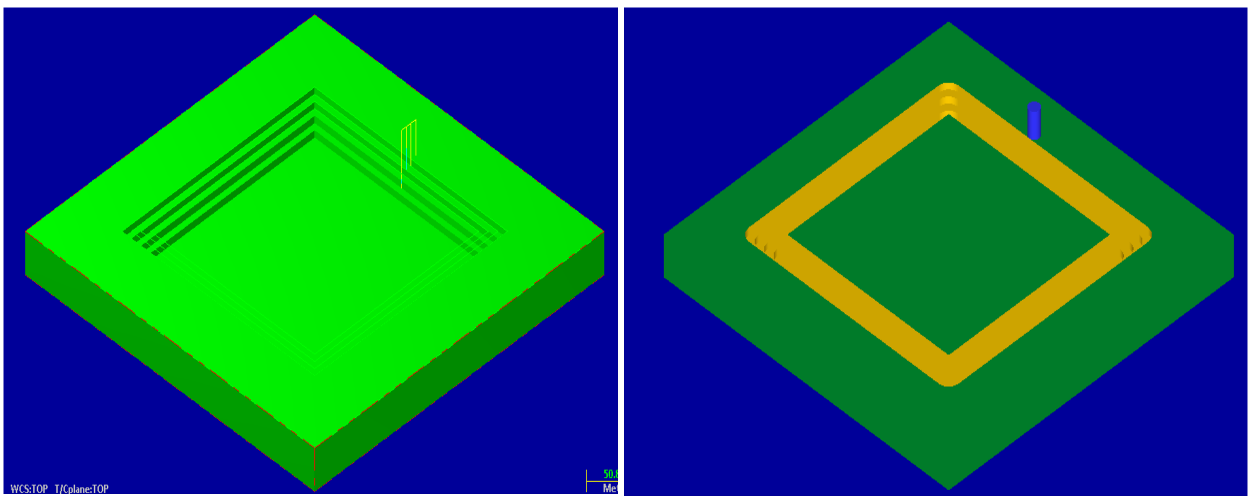


Figure 3. 12 a) master cam model for stock b) moment at which the tool as is cut the stock

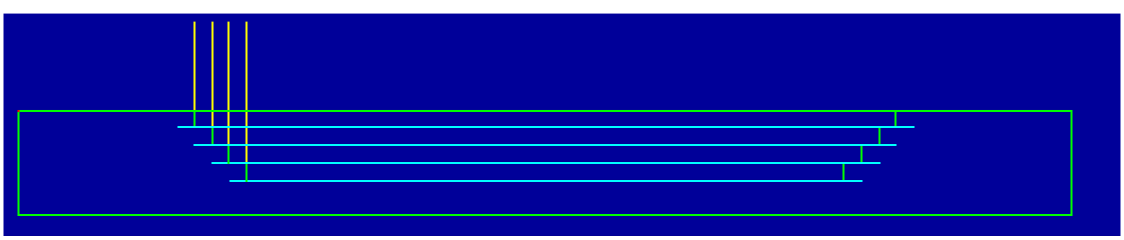


Figure 3. 13 Master CAM model for tool path that is the way tool incrementing with Δh

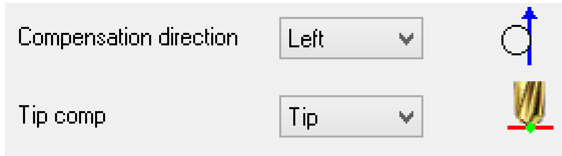


Figure 3. 14 Compensation direction and tip compensation

3.6 Dimension for Tool Paths

Dimension set required to direct the tool path from start point to end point, the paths are rectangular contours and parameter of the rectangle decreases each time the tool increment.

Below the calculation show as the tool incrementing by 0.6mm, 1mm, and 1.2mm.

Fig. 3.15a show where the angle $\alpha = 60^0$ is wall angle obtained from the slope tool movement measured with horizontal.

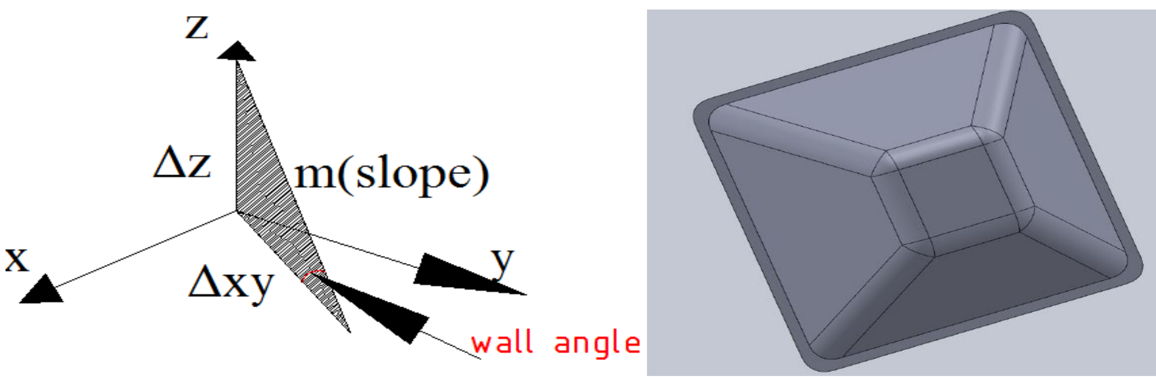


Figure 3. 15 Shows wall angle formed (a) and the desired shape at the end of the process (b)

<u>Test 4</u>

t_0 = 2mm, r = 10, Δh = 0.6mm , $\alpha = 60^0$

M(slope) = $\frac{\Delta y}{\Delta x}$ = tan α

$\Delta y = \Delta h = 0.6$ mm

Tan60^0 = $\frac{0.6}{\Delta xy}$ = 1.73

$\Delta xy = 0.3468 \rightarrow \Delta xy = \sqrt{x2 + y2}$; since x=y

$\Delta xy = \sqrt{2x2} = 0.3468$

X=y= 0.245

<u>Test 5</u>

t_0 = 2mm, r = 10, Δh = 1mm , $\alpha = 60^0$

M(slope) = $\frac{\Delta y}{\Delta x}$ = tan α

Δy = Δh = 1 mm

Tan60^0 = $\frac{1}{\Delta xy}$ = 1.73

Δxy = 0.578➔ Δxy =$\sqrt{x2\ +\ y2}$; since x=y

Δxy = $\sqrt{2x2}$ = 0.578

X=y= 0.408

<u>Test 6</u>

t_0 = 3mm, r = 8, Δh = 1.2mm , α =60^0

M(slope) = $\frac{\Delta y}{\Delta x}$ = tan α

Δy = Δh = 1.2 mm

Tan60^0 = $\frac{1.2}{\Delta xy}$ =1.73

Δxy = 0.693 ➔ Δxy =$\sqrt{x2\ +\ y2}$; since x=y

Δxy = $\sqrt{2x2}$ = 0.693

X=Y= 0.49 mm

The dimension for rectangular contour for three tests and their calculation for the X and Y values and Z value (step depth) is written in the above calculations Table 3.5 shows the tabulated data format for test 5, 6 and 7. Fig. 3.16 trajectory tool movement as the tool steps down by step depth using Master CAM simulating software. The unit system is metric unit system so that every move is counted in millimeter unit. The incremental depth is given in absolute motion so that if the first increment is 1.2 mm down then second increment shows 2.4 mm down the third increment is 3.6 finally the forth increment 4.8 mm it continue the increment this way.

Table 3. 5 Show dimension of each rectangular contour and maximum depth

Contour number	Test 4	Test 5	Test 6
H(step depth)	0.6	1	1.2
θ(wall angle)	60	60	60
1st contour	200	200	200
2nd contour	199.51	199.184	199.02
3rd contour	199.02	198.368	198.04
4th contour	198.53	197.552	197.06
5th contour	198.04	196.736	196.08
6th contour	197.55	195.92	195.1
7th contour	197.06	195.104	194.12
8th contour	196.57	194.288	193.14
9th contour	196.08	193.472	192.16
10th contour	195.59	192.656	191.18
11th contour	195.1	191.84	190.2
12th contour	194.61	191.024	189.22
13th contour	194.12	190.208	188.24
14th contour	193.63	189.392	187.26
15th contour	193.14	188.576	186.28
16th contour	192.65	187.76	185.3
17th contour	192.16	186.944	184.32
18th contour	191.67	186.128	183.34
19th contour	191.18	185.312	182.36
20th contour	190.69	184.496	181.38
21st contour	190.2	183.68	180.4

Contour number	Test 4	Test 5	Test 6
22nd contour	189.71	182.864	179.42
23rd contour	189.22	182.048	178.44
24th contour	188.73	181.232	177.46
25th contour	188.24	180.416	176.48
26th contour	187.75	179.6	175.5
27th contour	187.26	178.784	174.52
28th contour	186.77	177.968	173.54
29th contour	186.28	177.152	172.56
30th contour	185.79	176.336	171.58

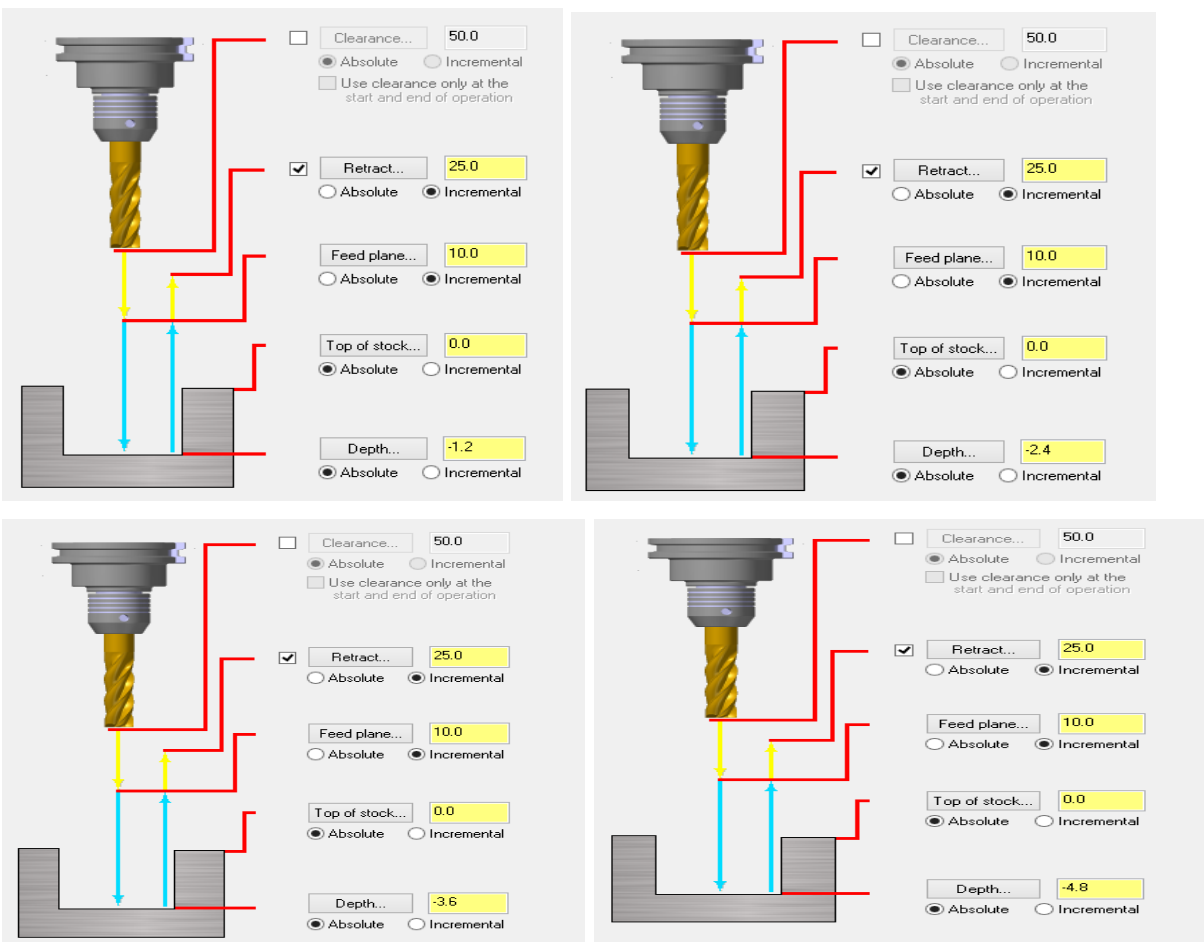


Figure 3. 16 Trajectory tool movement as it step down a) first contour with -1.2 depth b) second contour with -2.4 depth c) Third counter with -3.6 depth D) Fourth counter with -4.8 depth

3.7 G-Code Genration

Below we can see G code and M code generate using Master CAM similar with the simulation done.Besides to G and M code it include other parameters like feed, spindle speed, tool number, tool offset, date and time prepared. For all code generated fromN100 to N210 detail explanation was given.

Below we present one generated code using Master CAM from 16 tests we represent as a sample that is test 16.

%

(test 6)

(DATE=DD-MM-YY - 09-02-17 TIME=HH:MM - 03:35)

(MCX FILE - T)

(NC FILE - C:\USERS\USER\DESKTOP\EXPEMENT 6.NC)

(MATERIAL - ALUMINUM MM - 1050)

(T219 | 10. FLAT ENDMILL | H219)

N100 G21

- ⇨ [G21 6 Metric Data Input (Milli metres)]

```
N102 G0 G17 G40 G49 G80 G90
```

- ⇨ GØØ Positioning (Rapid Traverse)
- ⇨ G17 use xy plane as a reference plane
- ⇨ G4Ø Cutter Compensation Cancel
- ⇨ G49 Tool offset decreases
- ⇨ G8Ø Canned Cycle Cancel
- ⇨ G9Ø Absolute Zero Command

```
N104 T219 M6
```

- ⇨ T219 tool number 219
- ⇨ M6 Tool change/retract

```
N106 G0 G90 G54 X-100. Y-100. S38 M3
```

- ⇨ GØØ Positioning (Rapid Traverse) to position X-100. and Y-100.
- ⇨ G9Ø Absolute Zero Command
- ⇨ G54 maximum speed setting
- ⇨ S4 spendle speed is 38

⇨ M3 spendle speed on clock wise direction

N108 G43 H219 Z25.

⇨ G43 Tool radius compensation is to right

⇨ H219 Tool offset

⇨ Z25. Retract height is 25mm

N110 Z10.

⇨ Z10. Feed plane 10mm

N112 G1 **Z-1.2** F3.6

⇨ G1 Linear interpolation(Feed) to the value of **Z-1.2**

⇨ F3.6 feed rate is 3.6mm/s

N114 Y100.

⇨ Linear interpolation(Feed) to the value of **Y96**

N116 X100.

⇨ Linear interpolation(Feed) to the value of **X96**

N118 Y-100.

⇨ Linear interpolation(Feed) to the value of **Y-96**

N120 X-100.

⇨ Linear interpolation(Feed) to the value of X**-96**

N122 G0 Z25.

⇨ GØØ Positioning (Rapid Traverse) to position X-96. , Y-96 and Z25

N124 X-99.51 Y-99.51

⇨ GØØ Positioning (Rapid Traverse) to position X-95.85 Y-95.85and Z25

N126 Z10.

⇨ GØØ Positioning (Rapid Traverse) to position X-95.85 Y-95.85and Z10

N128 G1 **Z-2.4**

⇨ G1 Linear interpolation(Feed) to the value of X-95.85 Y-95.85and **Z-2.4**

N130 Y 99.51

⇨ G1 Linear interpolation(Feed) to the value of X-95.85 Y95.85and **Z-2.4**

N132 X 99.51

⇨ G1 Linear interpolation(Feed) to the value of X95.85Y95.85and **Z-2.4**

N134 Y-99.51

⇨ G1 Linear interpolation(Feed) to the value of X95.85 Y-95.85and **Z-2.4**

```
N136 X-99.51
```

⇨ G1 Linear interpolation(Feed) to the value of X-95.85Y-95.85and **Z-2.4**

```
N138 G0 Z25.
```

⇨ GØØ Positioning (Rapid Traverse) to position X-96. 85, Y-96.85 and Z25

```
N140 X-99.02 Y-99.02
```

⇨ GØØ Positioning (Rapid Traverse) to position X-95.701 Y-95.701 and Z25

```
N142 Z10.
```

⇨ GØØ Positioning (Rapid Traverse) to position X-95.701 Y-95.701 and Z10

```
N144 G1 Z-3.6
```

⇨ G1 Linear interpolation(Feed) to the value of X-95.701 Y-95.701 and **Z-3.6**

⇨ {.
.
.

```
N194 G91 G28 Z0.
```

⇨ G91 Incremental Programing

⇨ G28 Return to the reference point z0

```
N196 G28 X0. Y0.
```

⇨ G28 Return to the reference point X0. Y0

```
N198 M30
```

⇨ M30 end of data

```
%
```

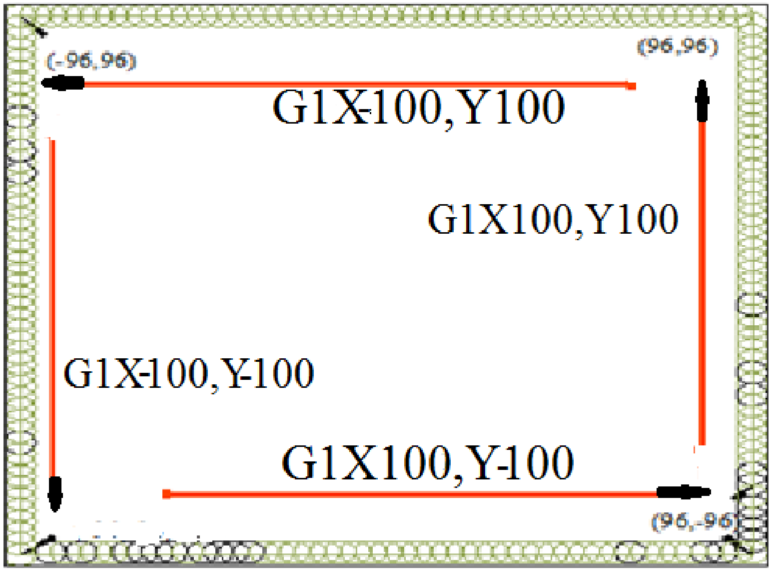


Figure 3. 17 Tool Path Movement as the tool moving the first Contour

3.8 Description for the Tool Movement

The movement for tool is generated by master cam x5 as showen above it genrated, so that it can be desciptive for total tool to go from starting point to end. The Fig. 3.17 shows how the tool moves from staring pont at (-100,-100) once the tool goes -1.2 mm along negative z axis.

The small circle reprsents the tool as it was seen from the above.The outer rectangle has a diamension 200mm*200mm. since the tool have 8mm diamter it needs an offsset from the desired rectangle. In order to get 200mm by 200mm net size we need to have 4mm ofsset the left as shown below.

Then the tool moves to the second point at (-99.51,- 99.51) and the tool goes in depth up to -2.4 mm along negative z axis. Then the tool follow the second rectangle as the contour staring from (-99.51,- 99.51,-2.4).The rest rectangular contour repaet the G code and M code only changing the diamensions of each rectangle coordinate system.

Consequntely the tool follow the remaining rectanges like the above two paths the it continus the same way. As shown below in Fig. 3.18 the movement of the tool continues till the end of the program or the final Contour.

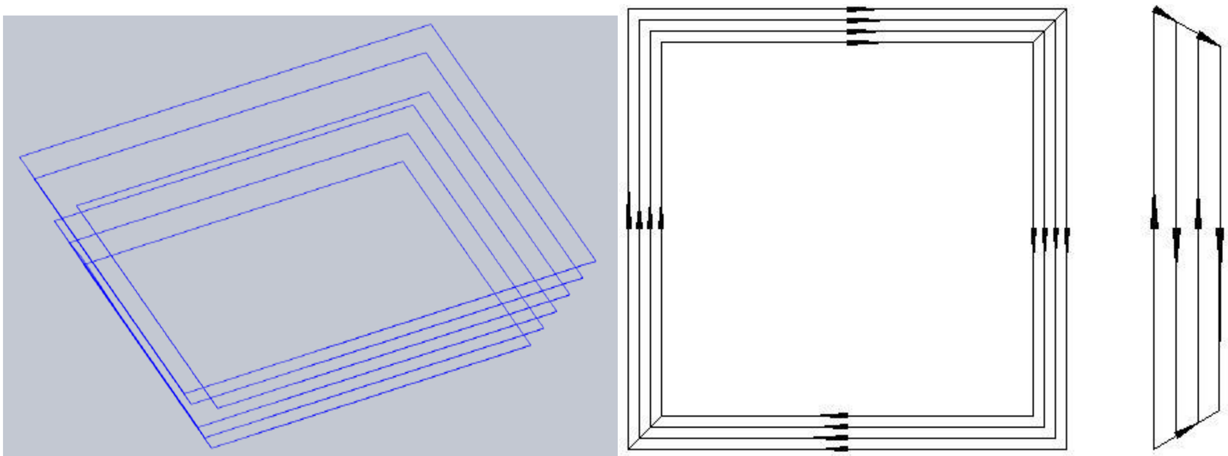


Figure 3. 18 The tool moves continuously many contours repeatedly

CHAPTER FOUR

4.1 Results and Discussion

After completing the process parameters the result is organized in a tabular shows the effects of parameters these on the forming process single point incremental forming process of sheet metal. The result obtained from the explicit modeling and simulation software called ABAQUS 6.13.

Damage conditions that initiate a crack can be based on either maximum principal stress or maximum principal strain. Maximum stress can obtained in ABAQUS result that occur in the sheet shows that the forming process within the limit of plastic region or the sheet is under crack region and also the effect of different parameters on the result.

Figure 4. 1 Experimental result obtained after conducting the experiment

After completing the full analysis and nodal output packager in job module. Taking around an hour to complete all 150 steps for 30 contours each contour 0.6, 1 and 1.2 mm incremental depth the stress result for the three incremental depths appears as shown in the Fig. 4.2 to 4.4.

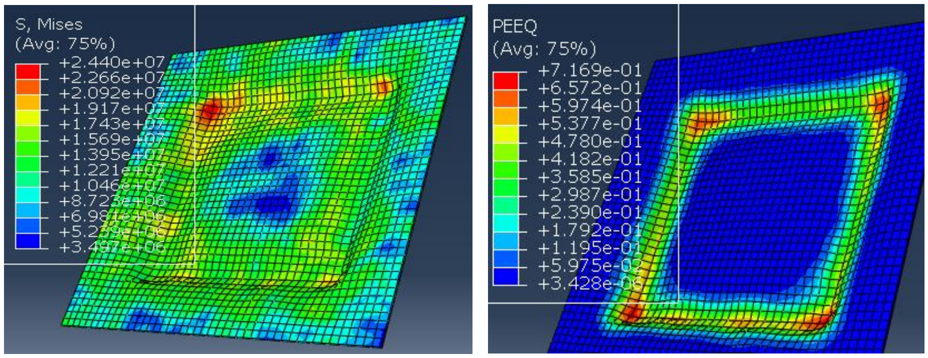


Figure 4. 2SPIF process with an incremental depth of 0.6

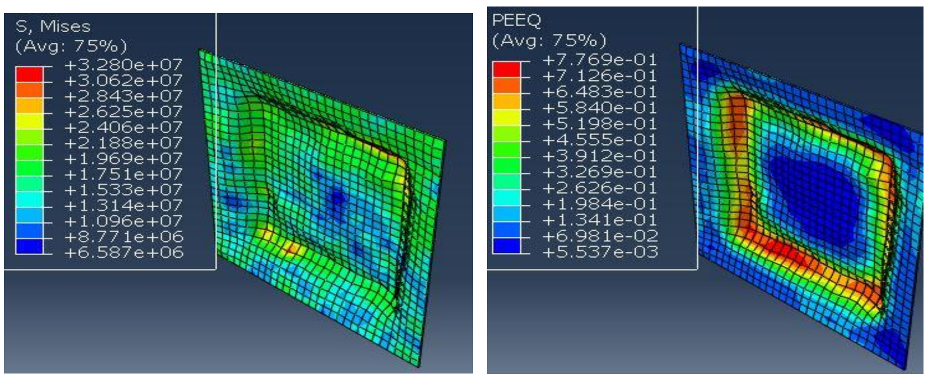


Figure 4. 3 SPIF process with an incremental depth 1mm

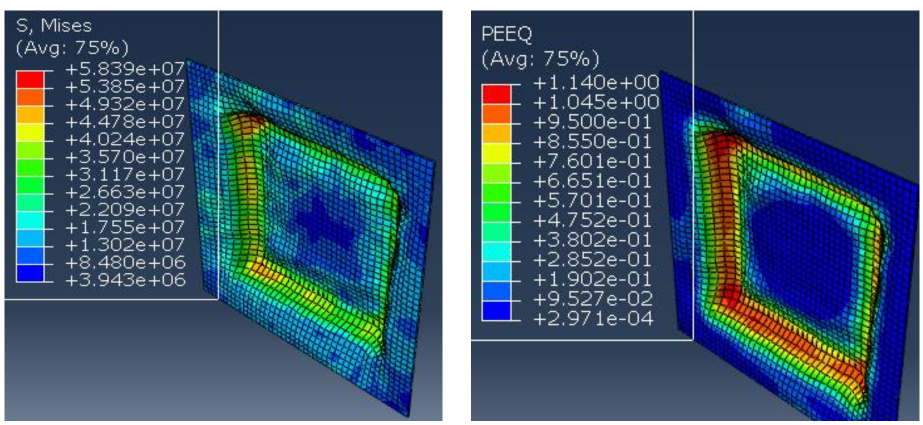


Figure 4. 4 SPIF process with an incremental depth 1.2

In order to make the same depth we made additional scenario for the three incremental depths to make 1.8 cm. we need to make 30contours, 18 contours and 15 contours for 0.6mm, 1mm and 1.2incremental depth respectively. The Fig 4.5 and Fig 4.6 describe for 18 contour with 1 mm increment and 15 contour tool path with 1.2 mm increment.

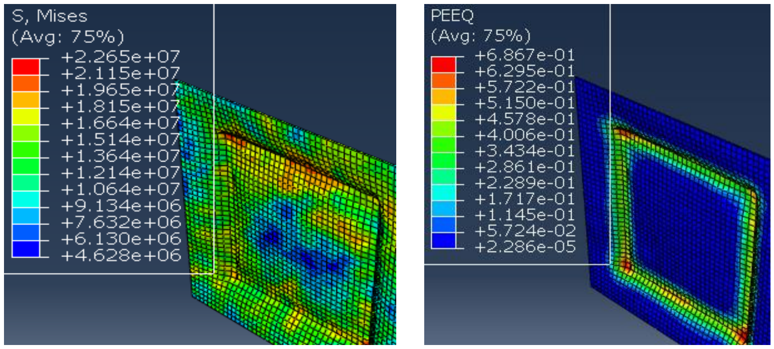


Figure 4. 5 incremental depth 1.2mm with18 contours

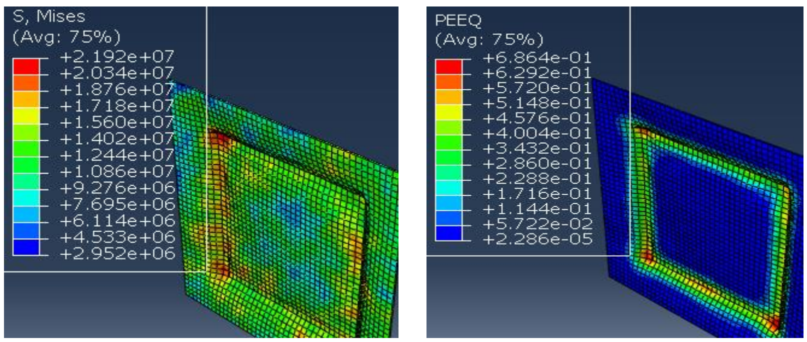


Figure 4. 6 Incremental depth1.2mm with 15 contours

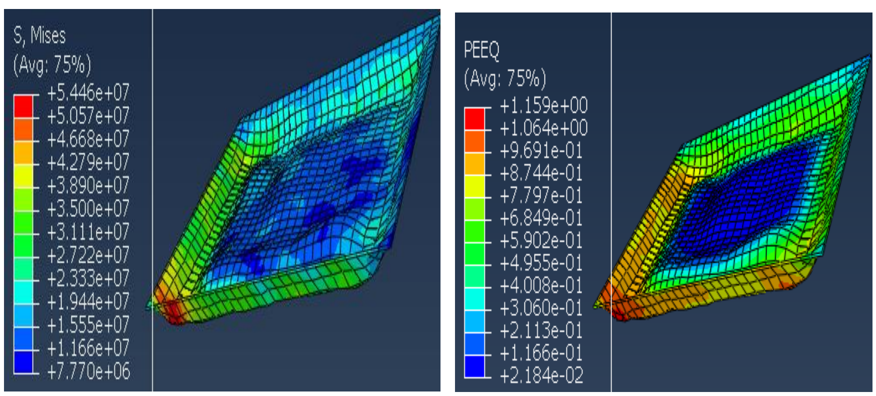


Figure 4. 7 Effect forming while making the shortest distance 2.5 cm from sides of the fixator

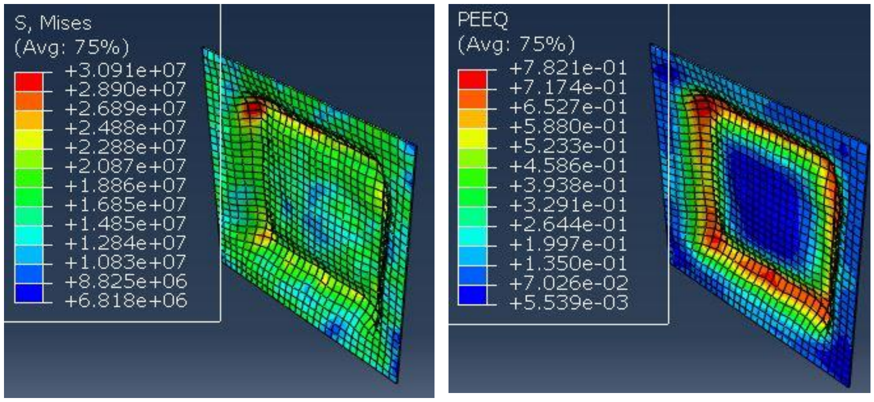


Figure 4. 8 The result obtained as the tool rotates 50rad/s

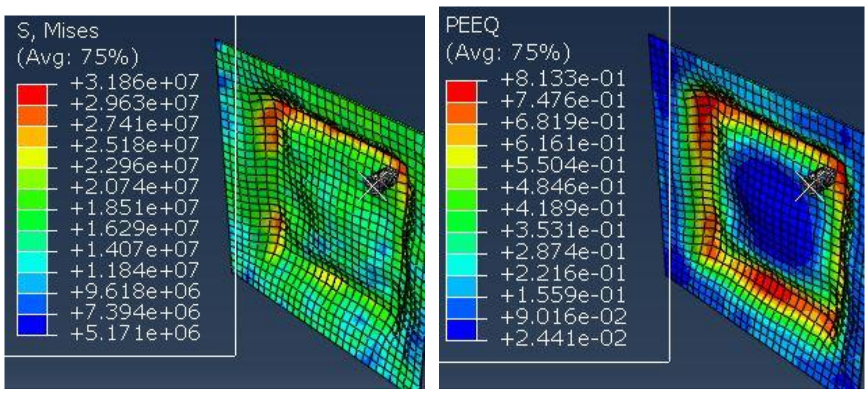


Figure 4. 9 The result obtained as the tool rotates 100rad/s

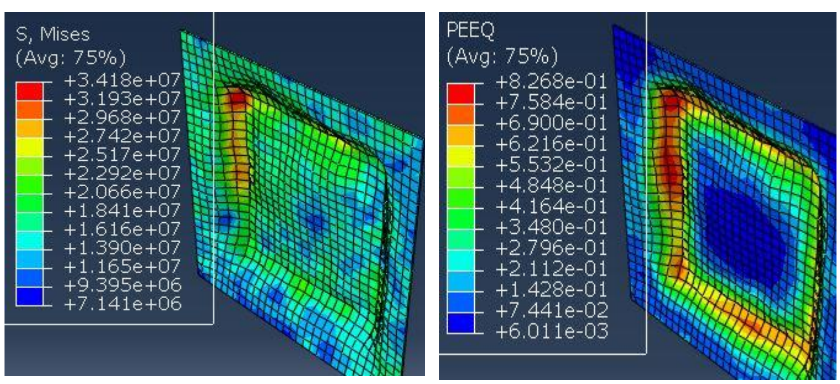


Figure 4. 10 Result obtained while using a tool 10mm diameter

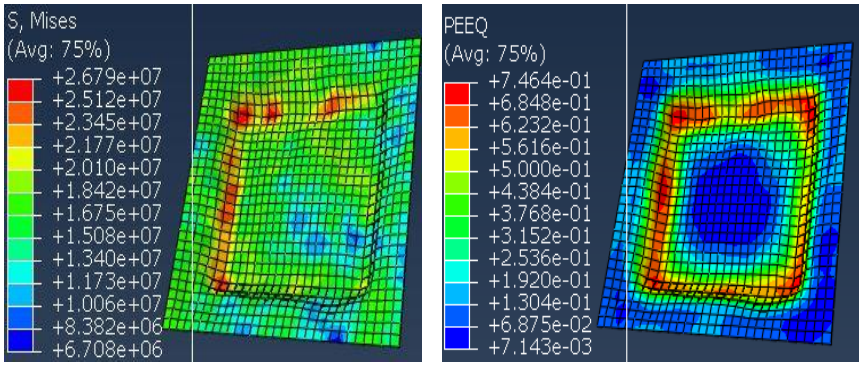


Figure 4. 11Result obtained while using a tool 18mm diameter

Table 4.1 Shows ABAQUS result for von misses stress (s) and equivalent plastic strain (PEEQ) with respect to change in incremental depth of the punch after making 30 contour tool paths that is each contour have five steps. A total of 150 steps needed to complete 30 rectangular contours each step describe the movement of the tool.

Table 4. 1 Effect incremental depths with respect to stress and equivalent strain

Experiment number	Incremental depth (mm)	Von misses stress (MPa)	equivalent plastic strain **(**PEEQ**)**
1	0.6	24.4	0.7169
2	1	32.8	0.7769
3	1.2	58.3	1.1

The effect of incremental depth on the forming process keeping constant other parameters like sheet thicken 2mm, tool radius 8 mm and rotational speed 0. We can see from The graph below Fig. 4.12 shows the stress level increases as the step depth increases for change in incremental depth of 0.6 mm von mises stress is 24.4 MPa, for 1mm von mises stress is 32.8 MPa, and for 1.2 mm von mises stress is 58.3 MPa. As we see from the graph as we increase the incremental depth so that the stress level increased due to large deformation and large strain takes place too. For 0.6 mm the von mises stress level is 24.4 MPa, so the sheet under this stress is not damaged i.e the micro structure is nearly similar since the stress to small compared to ultimate stress. But the maximum depth it form is 1.8cm which is too small compared to the two process. For 1mm and 1.2 incremental depth the stress level reach 32.8 MPa and 58.3 MPa respectively this shows the stress get high while increasing the step depth. Meanwhile the maximum depth increases from 3cmm for 1mm step depth and 3.6cm for 1.2mm step depth.

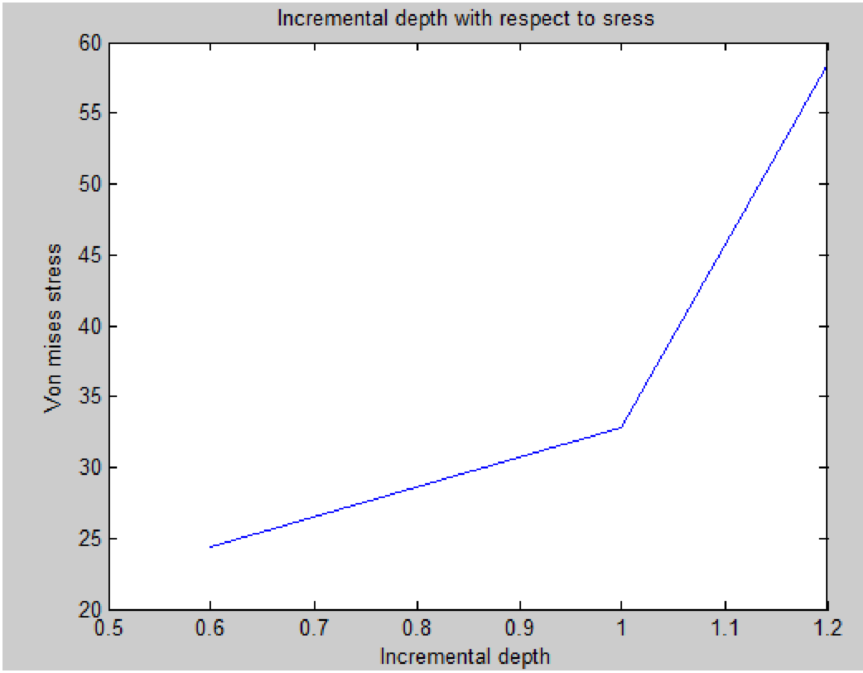


Figure 4. 12 Graphical representation for von misses stress with incremental depth

Table 4. 2 Effect tool rotations with respect to stress and equivalent strain

Experiment Number	Rotational speed (rad/s)	Von misses stress (MPa)	equivalent plastic strain **(**PEEQ**)**
4	0	32.8	0.7769
5	50	30.91	0.7821
6	100	31.86	0.8133

The graph bellow fig 4.13 shows the effect for rotational speed in sheet metal forming process from zero rotational speed i.e 0 rad/s, 50 rad/s and 100rad/s. Keeping other parameters constant these are sheet thickness 2mm, tool radius 8 mm and incremental depth 1mm. The result of stress for zero rotational speed 0 rad/s the von mises stress is 32.8 MPa, for 50 rad/s (477.46rev/min) the von mises stress is 30.91 MPa and for 100rad/s the von mises stress is 31.86 MPa.

As we can see the graph on Fig 4.13 shows the stress level is decreases 0 rad/s than that of 50 and 100 rad/s tool rotation but the graph increases a little from 50 to 100 rad/s (954.92rev/min). We can understand from the graph the stress value decreases as we apply rotation on the tool along the z-axis or center of the tool i.e the stress at zero rotation is 32.8MPa to 30.91MPa this is due as tool rotating while moving along the path reduces the friction due to sliding friction changes to rolling friction between the sheet and tool. Again as we increase the rotational speed to 100 rad/s then the stress value increases to 31.81 MPa this is due to high rotation creates local deformation since too much rotating of the tool at a point develops local strain on the sheet metal eventually leads crack.

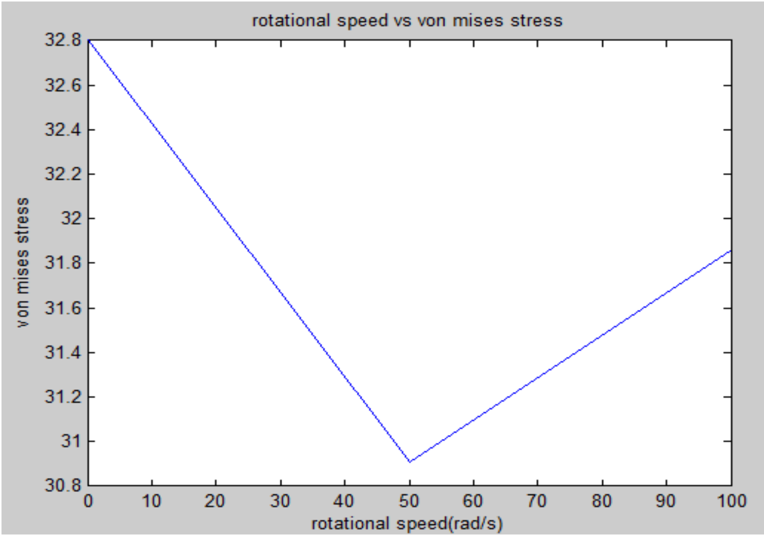


Figure 4. 13 Graphical representation for von misses stress with respect to tool rotation

Table 4. 3 The effect same depth of formed sheet using various step depth with respect to stress and equivalent strain

Experiment Number	Number of contours	Incremental Depth(mm)	Von misses stress (MPa)	equivalent plastic strain **(**PEEQ**)**
7	15	1.2	21.92	0.6864
8	18	1	22.65	0.6867
9	30	0.6	24.4	0.7169

In order to develop 1.8cm depth using different step depth i.e 0.6mm, 1mm and 1.2mm and we made 30 contours, 18 contours and 15 contour respectively. The experiment is done by keeping constant sheet thickness 2mm, 8mm tool radius. As we see the Fig. 4.14 below the stress and the strain value reduced while increasing the step depth and decreasing the number of contour due to the fact that with large distance gap the stress concentration is subdivided in to the gap. The von mises stress 24.4 MPa using 0.6mm step depth i.e 30 contours whereas the von mises stress is 21.92 MPa while using 1.2mm step depth and 15 contours. As the number of counter path increases the stress developed will be larger since frequent loading and unloading causes large stress to develop.

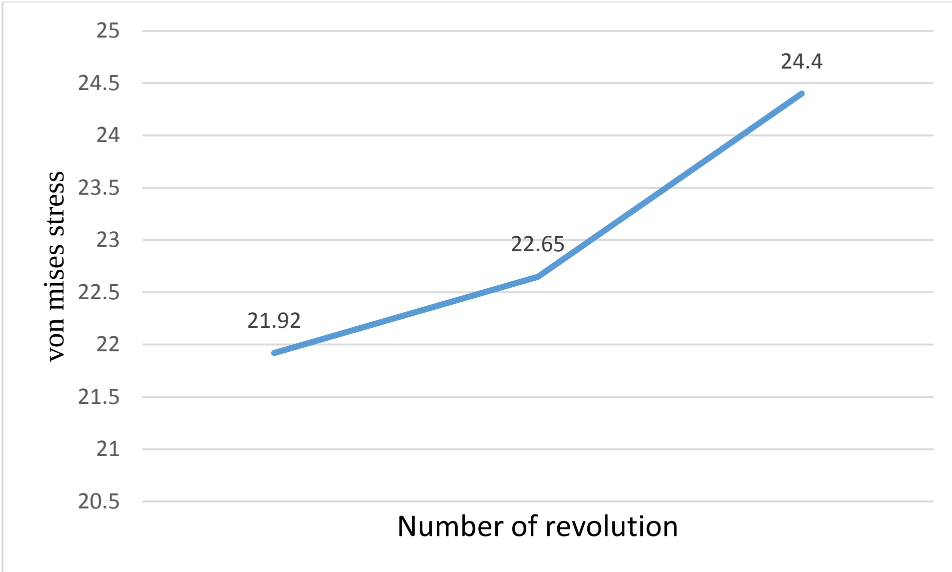


Figure 4. 14 Graphical representation for von misses stress with respect to depth to form the same depth of 1.8 cm

Table 4. 4 The effect tool diameters in the forming process with respect to stress and equivalent strain

Experiment Number	Tool diameter (mm)	Von misses stress (MPa)	equivalent plastic strain **(PEEQ)**
10	10	34.18	0.8268
11	16	32.8	0.7769
12	18	26.79	0.7464

Fig. 4.15 describe the effect of tool diameter on deformation of sheet metal, while the rest parameters incremental depth, sheet thickness and rotational speed is kept constant which is 1mm, 2mm and 0 rad/s respectively. At 10mm tool diameter the deformation von misses stress is 34.18 Mpa, at 16mm diameter the von misses stress is 32.28 Mpa, at 18mm diameter the von misses' stress is 26.79 Mpa. Since the all stress levels are under work hardening region is in the range from 20Mpa to 70 Mpa that means the deformation is in plastic region the deformation is not reversible. The larger the diameter the lower it became the stress level so increasing the tool radius decreases the occurrence of the crack region. Smaller tool can easily deform the sheet metal easily but it is sensitive to the crack the sheet since the stress develop is too large compare larger tool diameter.

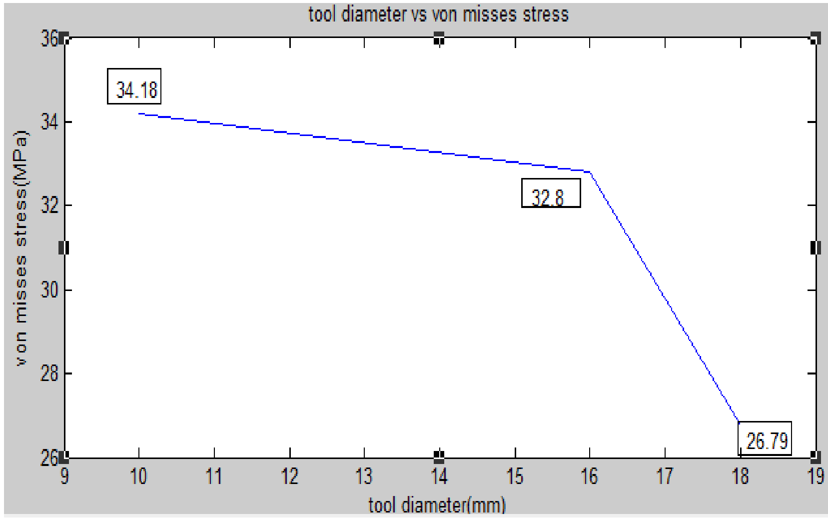


Figure 4. 15 Graphical representation for von misses stress with respect to tool diameter

From the below Table 4.5 it shows effect of the starting point of the tool that is as the tool begins near to the fixture develops high stress and maximum strain value. The experiment conducted the sheet thickness 2mm, tool radius 8mm, step depth 1mm. As the tool begins 2.5cm shortest distance from each sides of the fixture the stress is 54.46 MPa and the equivalent strain is 1.159 whereas as the tool begins at 5cm the stress value is reduced to 32.8 MPa and the strain value is 0.7769. Therefore as the distance of the tool from each of sides of the fixture as it gets shorten then increased the stress and strain value reduced vice versa. The two experiment is used fully describe effect of tool distance with respect to the fixture.

Table 4. 5 The effect distance of the tool from the fixture with respect to stress and equivalent strain

Experiment Number	Shortest distance of the tool from the fixture (cm)	Von misses stress (MPa)	equivalent plastic strain **(**PEEQ**)**
13	2.5	54.46	1.159
14	5	32.8	0.7769

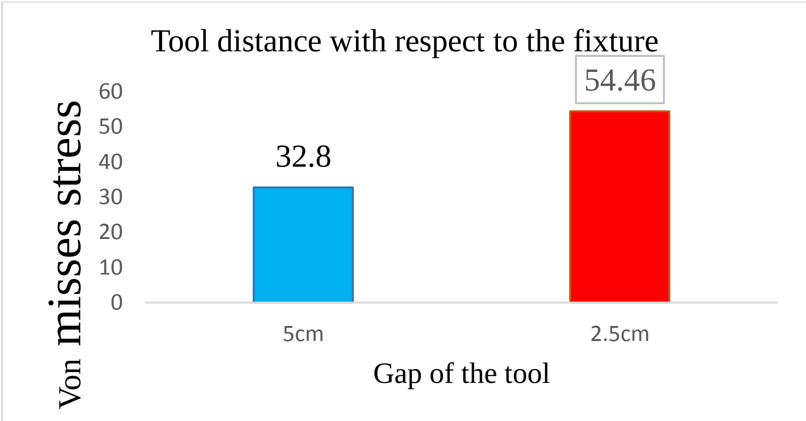


Figure 4. 16 the effect tool distance from the fixture

Fig. 4.17 shows plot for three parameters that affects the process incremental sheet forming. These includes graphs of tool versus radius stress, incremental height versus stress and rotational speed versus stress. As we see the graph Fig. 4.16 shows graphs slope made by step depth is steep slope from 24.4 to 58.3 MPa. That means the graph grows sharply that is a little change in the incremental height causes large change on the stress value. So step depth in a single point incremental forming process is sensitive parameter so that it is critical from three parameters.

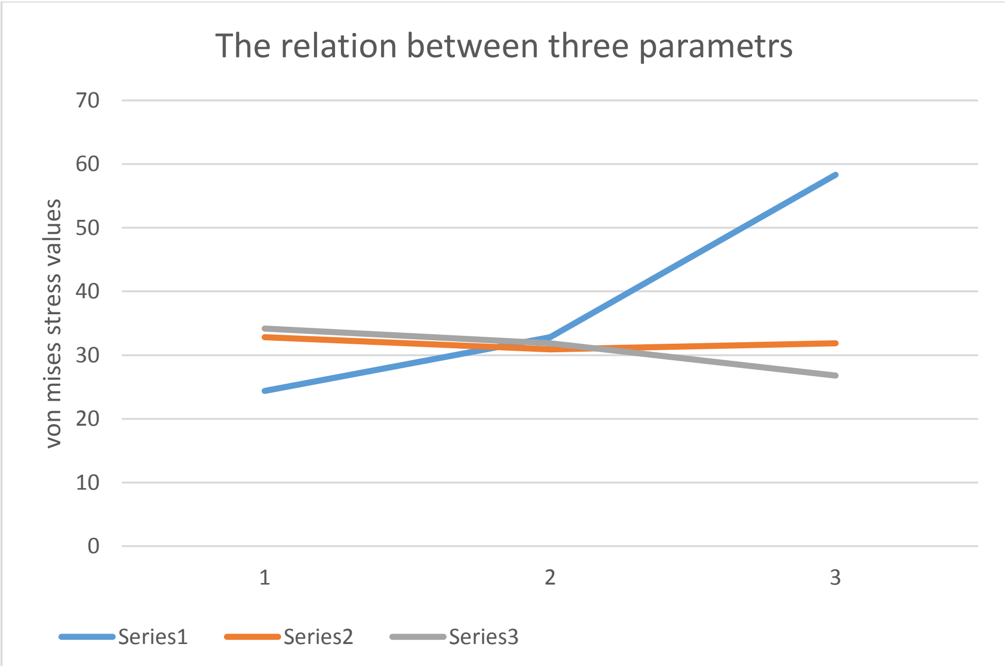


Figure 4. 17 the relation between different parameters set together

Fig 2.17 a & b shows the formed shape using 2 mm step depth for 30 contour it makes 6cm depth keeping the tool radius 8mm sheet thickness. The von mises stress 67.23 MPa which is very close with the ultimate stress value 70MPa and equivalent strain 1.248 beyond this failure occurs. Further increase in number of contour and step depth leads damage due to excessive stress and strain.

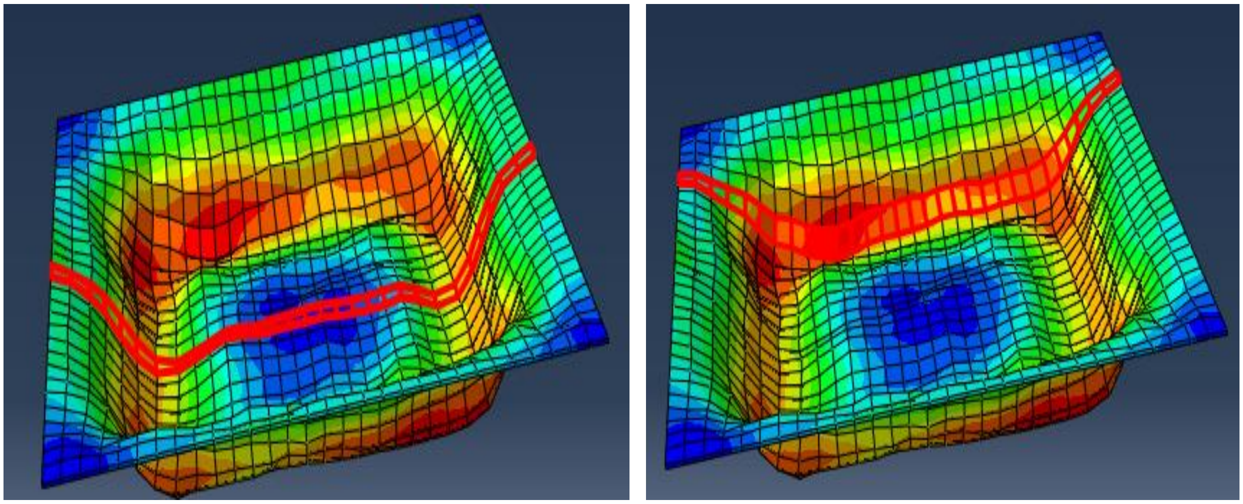


Figure 4. 18 (a) & (b) shows two striped region on both which vary in the value of stress and strain

Table 4. 6 represents strain distribution on pyramid with respect to mid-section and edge section

Elements No.	Mid-section of the pyramid	Elements No.	Edge section of the pyramid
182	0.476307	422	0.458598
184	0.843638	424	0.662477
186	1.0544	426	1.00545
188	0.75863	428	1.12924
190	0.451224	430	1.00193
192	0.28601	432	0.962476
194	0.185817	434	0.880419
196	0.177757	436	0.979326
198	0.161203	438	0.964287
200	0.240737	440	1.03777
202	0.463544	442	1.10842
204	0.903037	444	1.21992
206	0.989583	446	1.23973
208	0.569446	448	0.838516
210	0.509249	450	0.450209

Stain distribution shown 4.6 for Fig 4.17 (a) is at mid-section of the pyramid and Fig 4. 17(b) on the edge represents 15 elements each. The result for strain distribution was taking from experiment on ABAQUS result from end point to the opposite of the end point.

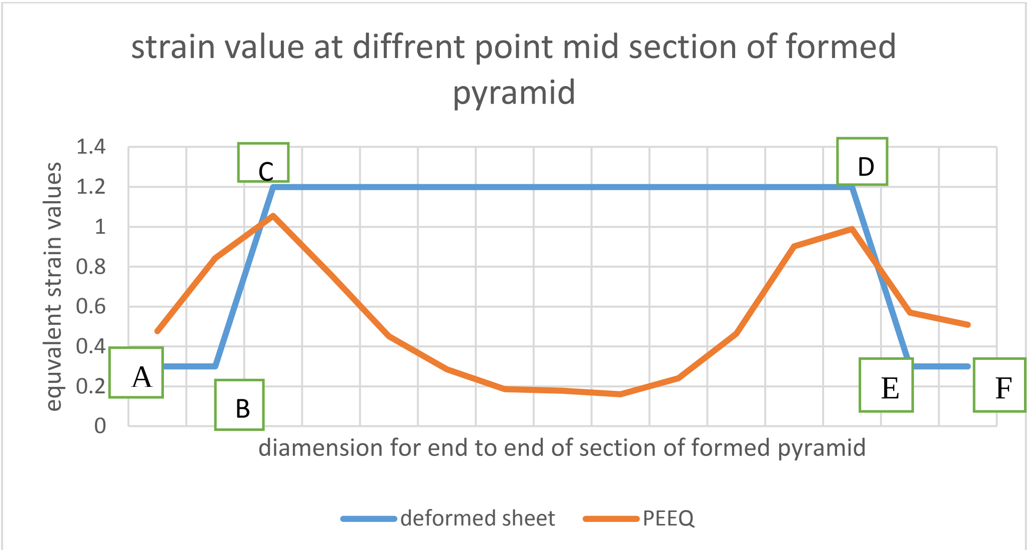


Figure 4. 19 the relationship between the strain value with the deformed shape of the pyramid for strip on Fig 4.18 a)

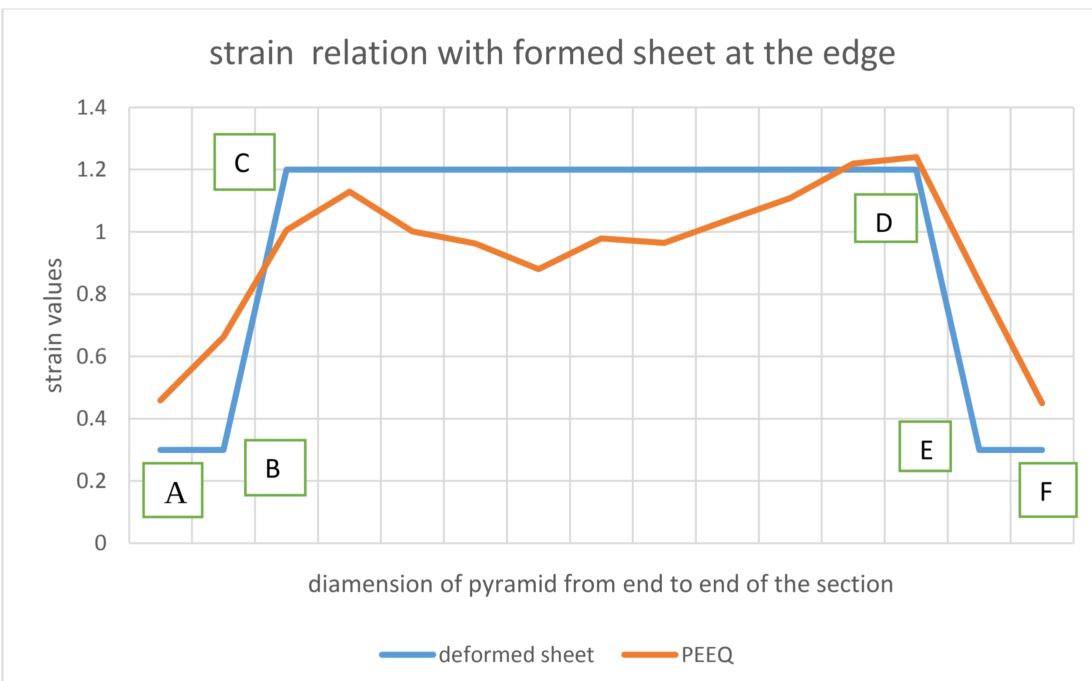


Figure 4. 20 the relationship between the strain value with the deformed shape of the pyramid for strip on Fig 4.18 b)

On Fig 4.17 a) the strip pass along the mid-section of the formed pyramid at this section high strain value is the corner of the pyramid shown by red band color. As we see from the Fig. 4.18 the strain value is lower at base part from C to D that is very little deformation take place. The second deformation occurs at fixture sides A to B and E to F. The maximum stress occur at the corner of section of the pyramid i.e at the region very close to the point C and D.

On the Fig 4.19 is drawn based on the Fig. 4.17 b) by taking strain result from points of the strip we draw the graph. These graph resemble the graph at Fig 4.18 except the strain result Fig. 4.19 at base section from C to D much larger than the strain result Fig 4.18. This is due to stress is higher in Fig 4.19 to the tool moves along the side wall of the base of C to D pyramid.

CHAPTER FIVE

Conclusions and Recommendation

5.1 Conclusions

The formability of aluminum (1050) to develop truncated pyramidal shaped object is evaluated using ABAQUS 6.13 finite element software. We carried out an experiment to through reduction in thickness of the sheet to manufacture a dish like product. In this study we have examined four critical parameters the formability affecting of incremental sheet forming processes are incremental depth, tool diameter, rotational speed of tool and geometric position of the tool with respect to the fixture. Hereby, we have summarized our results through the following points:

- The step depth play major role in performing the process for single point incremental forming process. A slight/little change in step depth significantly influences the stress and strain values. This means that an increase in step depth results increase in both stress and strain values. Therefore large step depth is deform the sheet easily but care should be taken to avoid damage or cracking on the sheet.
- The deformation rate has inverse relation with respect to tool diameter. Large tool diameter deforms the sheet less that of smaller diameter. Smaller tool deforms the sheet fast due to large stress and strain effect on the sheet. Large diameter deforms the sheet slowly but possible to produce much depth due to lower stress and strain effect.
- The tool with rotation and without rotation has effects the formation process of the sheet. This is because of tool rotation reduces excessive friction unwanted for SPIF process. Friction assist the forming process to some extent but excessive friction creates tearing on the sheet. Due to the presence of spindle rotation the friction type converted from sliding friction to kinetic friction.
- The distance of the tool with respect to the fixture of the sheet blank holding, affects incremental sheet forming process. The very short gap between the tool and fixture large stress and strain in the sheet develop. It is better to allow the optimum gap tool to start with the fixture.
- The strain concentration large at the edge of the formed pyramid and at the four corners of the formed pyramid.

5.2 Recommendations

- Further examination for SPIF process on other parameters that are not discussed here, like wall angle, spring back effect in a materials, and blank stiffness of materials, radius of blank holding device.
- Identify the effect of surface finish on finished product and develop reduction technique for surface roughness.
- Blank materials that other than aluminum and compare the result of the effect of process parameters.
- This SPIF processes to study on other components that forming process can be applied.
- Support the thesis with the experiment to compare and contrast the result with that of ABAQUS software as future work.
- In addition to SPIF two point forming process that uses mold and multi point forming process.
- Using SPIF add additional features to for finished products by other processes.
- SPIF process is similar with the spinning process in making similar shaped products to compare both processes.
- The tool used in SPIF is have to be checked for different shapes like flatten or ball that can roll and rotate on the sheet rather than fixed spherical.

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