Upper Bound Analysis of Single Point Incremental Forming

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The Degree of Master of Technology

Department of Mechanical Engineering

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Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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Approval Sheet

This thesis entitled "Upper Bound Analysis of Single Point Incremental Forming" by Chhavikant Sahu is approved for the degree of Master of Technology from IIT Hyderabad.

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"Dedicated to my Parents"

Abstract

Most of the conventional sheet metal forming processes uses expensive dies for forming sheet metals into final shape. This increases the cost of production. For eliminating these limitation one can utilize the new die less sheet metal forming process known as incremental sheet metal forming (ISMF). The process involves the use of a single spherical tool to carry out local sheet metal deformation progressively on a CNC milling machine. The controlled movement of the tool enables a 3-dimensional profile to be made. The process can provide rapid prototyping advantages for sheet metal parts which are made directly from a 3-D CAD model to finished product without the conventional intermediate stage of tool design and manufacture.

In this report the methodology of the Single Point Incremental Forming (SPIF) and Double Sided Incremental Forming (DSIF) processes are presented. Initially the CAD model of the final shape is produced then the STEP file is used to create tool path for the ISMF process by using tool path generating module. This tool path is then given as an input to the CNC machine and the desired motion of tool is obtained in order to produce the final shape. First the FEM analysis of Single Point Incremental Forming (SPIF) is done in order to analyze the deformation zone and the velocity fields. Then upper bound approach is used to study the deformation zone of SPIF. The velocity field and power dissipated are predicted using assumed deformation zone.

The incremental sheet metal forming has a potential application in field of aerospace and biomedical industries which are constantly looking for ways to reduce the weight and to improve the mechanical properties of parts and structures. The major advantage of ISMF technology is the possibility to manufacture sheet parts which are difficult to form with traditional processes in a rapid and economic way without expensive dies and long set-up times.

Key words: Incremental Sheet Metal Forming, Finite Element Analysis, Upper Bound Analysis, Deformation Zone

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Chapter 1

Introduction and literature review

1.1 Introduction

The conventional sheet metal forming process need part dependent tooling or dedicated dies, which costs in terms of time and money. The formability is also not much high in conventional sheet metal forming processes. Due to these factors along with increasing variety in the sheet metal forming, highly flexible forming processes are being developed. Incremental sheet metal forming is one of the emerging flexible forming technologies in the sheet metal forming processes, which rather uses universal tooling that is mostly part dependent. Hence the process offers higher flexibility reducing the product development greatly and making it suitable for low volume production. Incremental sheet forming has provided its great potential to form complex three dimensional parts without using a component specific dies.

Incremental sheet forming is a manufacturing process done usually with a solid, small sized tool being in continuous contact with a small deforming zone of the sheet without any dedicated die determining the shape of the component [1]. Initially this process is performed on a CNC milling machine-tool with CAD/CAM support. But now a dedicated DSIF machine is developed in which a small ball ended tool is being used, which can form the sheet metal that is rigidly fixed.

The incremental sheet metal forming can be mainly performed in two ways, Single Point Incremental Forming (SPIF) and Double Sided Incremental Forming (DSIF). In the SPIF process, freeform shapes can be produced using CNC controlled spherical tool. The process starts from a flat sheet metal blank, rigidly clamped on a platform. To form a part, the machine tool follows a pre-programmed contour, similar to a conventional milling operation. The main advantage of this method is that no dies are required**,** making this an ideal process for rapid prototyping or small batch production. Some samples of parts produced by incremental sheet metal forming are shown below in figure 1.1.

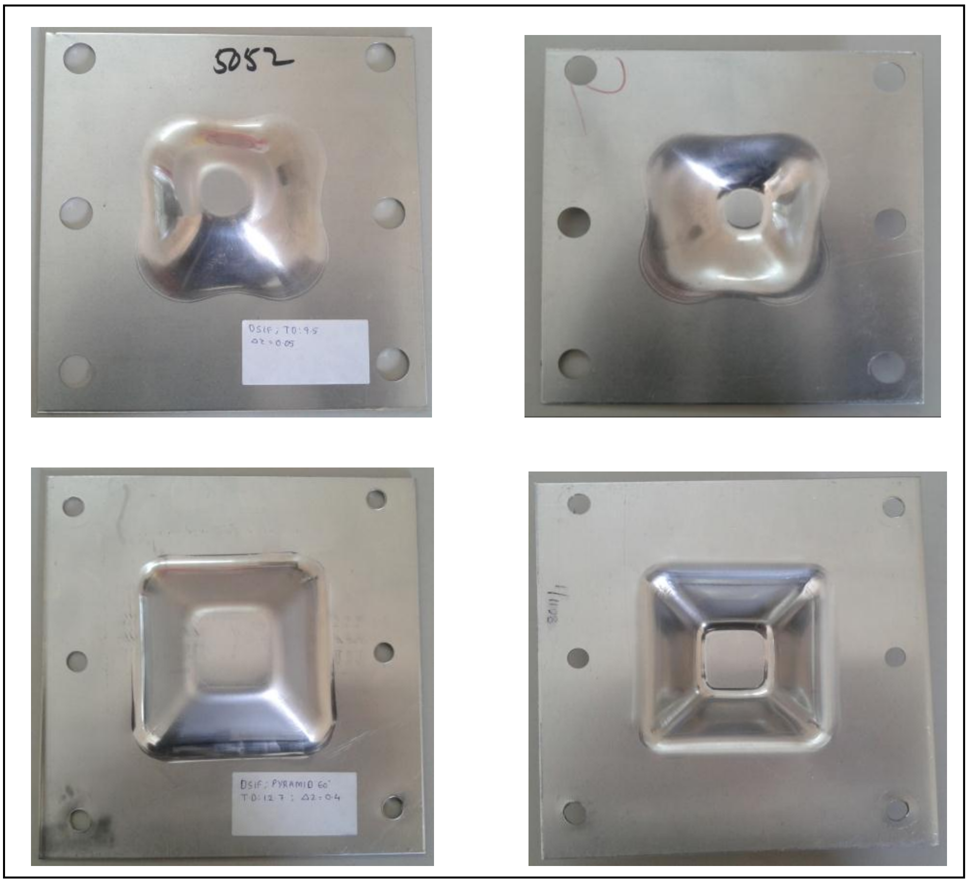
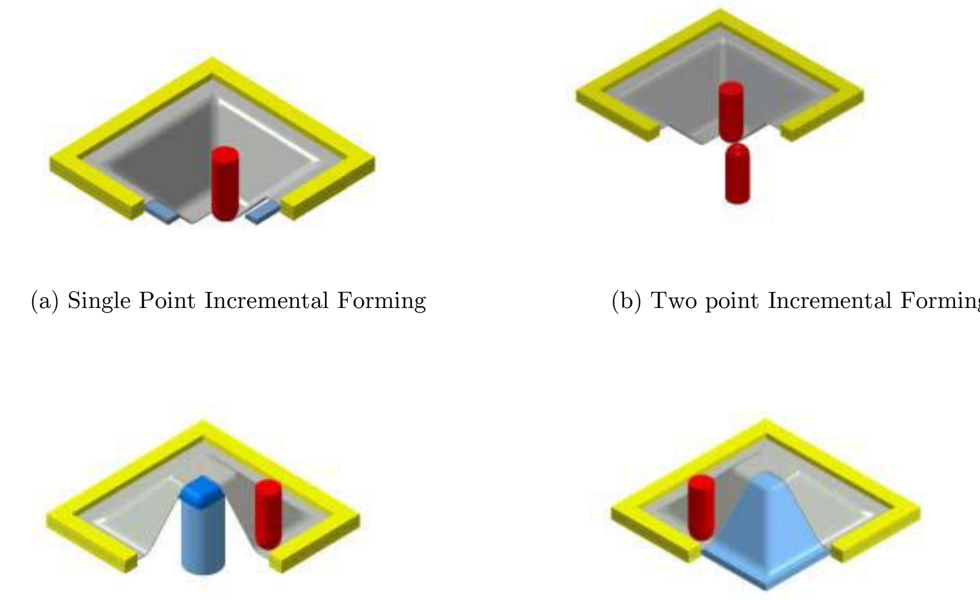


Figure 1.1: A sample of manufactured parts in ISMF

Today, the ISMF process is still premature and needs further development before it can be used for industrial applications. As recent market analysis studies have shown, accuracy is one of the most important limiting factors for the deployment of SPIF in industrial applications. So with better research one can bring the ISMF process with a great potential for industrial application.

Configuration of incremental forming processes

The incremental sheet metal forming techniques (ISMF) can be divided into two categories: two points incremental forming (TPIF) and single point incremental forming (SPIF), also known as positive and negative forming, respectively.



(a) Single Point Incremental Forming (b) Two point Incremental Forming

(c) Two point incremental forming (partial die) (d) Two point incremental forming (full die)

Figure 1.2: Process principles of ISMF (Jeswiet et al. 2005) [1]

In the TPIF process the sheet metal moves vertically on bearings, which move on sheet holder posts, along the z-axis, as the forming tool pushes into the metal sheet. This process is called TPIF because it has two contacting points between forming tool and the sheet. The first point where forming tool presses down on the sheet metal to cause locally plastic deformation. The second point is the contacting point between a static post and the sheet. The process principles of ISMF are shown in figure 1.2.

1.2 Literature review

Sheet metal forming is a major manufacturing process in many civil and industrial sectors. A new sheet metal forming process known as Single Point Incremental Forming (SPIF) has shown more flexibility in forming capabilities and having low operating costs. It does not require any dedicated dies. Due to its many advantages, in the recent years, there was a significant research activity in incremental sheet forming.

1.2.1 Studies on tool Path planning

ISMF process depends strongly on the forming tool path which influences greatly the part geometry and sheet thickness distribution. Tool path generation has direct impact on the dimensional accuracy, surface finish, formability, thickness variation and processing time.

There are two tool path strategies that are widely in use. One is contour tool path and the other is helical/spiral tool path as shown in figure 1.3. A spiraling tool path is continuous with incremental descent of the tool distributed over the complete contour of the part .The advantage is that no marks occur at step down. The parts formed by spiral tool path have a more uniform thickness distribution as compared to those formed by conventional contour tool path. [2]

Multi pass tool path strategies include creating intermediate forms that are defined within the cavity of the final surface and are typically characterized by limited slope angles and curvature. A challenge in Multi-Pass Single Point Incremental Forming (MSPIF) has been the geometry control of formed components, especially on the base of the component where multiple stepped features are formed unintentionally. Malhotra et al. [3] attributes the step formation to the rigid body motion during the forming process and develops analytical formulations to predict such motion during each intermediate pass. Based on this model, a new tool path generation strategy is proposed to achieve a smoother component base by using a combination of in-to-out and out-to-in tool paths for each intermediate shape.

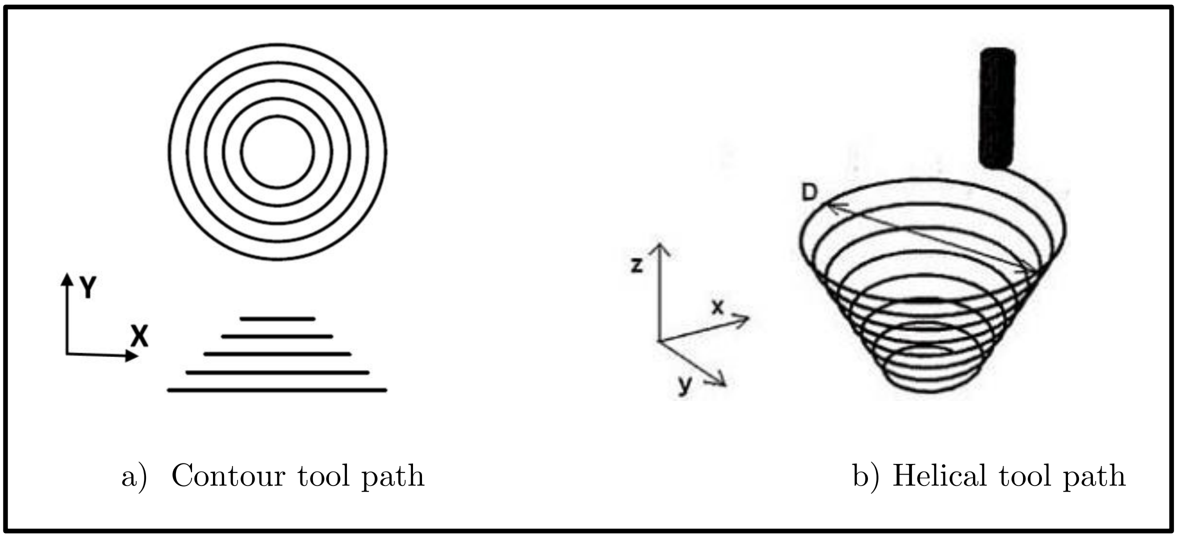


Figure1.3: Tool paths for ISMF [4]

1.2.2 Formability studies

Apart from tool path planning another important factor of ISMF is the formability of formed components. Stress and strains required to be calculated in the component, stresses in the component are used to predict the formability of the component using various models of ductile fracture and applicability of each model has been theoretically verified. Fracture limit curves have been drawn using the maximum formability limits.

Alwood et al. [5] reported that in the plane parallel to the tool path, the deformation is due to stretching and bending and in the plane perpendicular to the tool path, deformation is through thickness shear. Due to presence of through thickness shear, it was explained that tensile stresses responsible for failure get reduced and hence result in greater forming limits.

Martins et al.[6] proposed a membrane analysis to find the process mechanics of incremental forming in which they evaluate state of stress and strain in localized deformation zone around the tool. They assumed the material deforms only by plain strain stretching and neglected friction between tool and sheet. Based on these they obtained expressions for state of stress and strain for the material being formed and concluded that formability is expected to go down when sheet thickness decreases or tool diameter increases .in addition strain hardening was advantageous in terms of formability in incremental forming.

1.2.3 Forces in incremental sheet metal forming

Incremental forming process is still in development and requires much more research to reach a point where accuracy becomes comparable to some of the industrial process. Achievement of this goal will not be possible without better understanding of the process mechanics and influencing parameters. Magnitude of the forces between tool and work piece is of importance for the development of process models for single point incremental forming. [7]

Prediction of forming forces is essential to design tools and to determine the necessary power of the machine. Iseki obtained the forming forces for the incremental forming of the pyramid using a simply approximate deformation analysis. The plane strain deformation was assumed and this assumption was verified using a finite element method (FEM). [8]

1.2.4 The mechanics of incremental sheet metal forming

The experimental evidence and analysis concluded that, the formability of ISF process is mainly influenced by five major parameters: incremental depth, tool feed rate, tool diameter, sheet thickness and wall angle. The influence of sheet thickness and incremental depth were explained through sine law. A relationship between the wall thickness after forming (t_1) with the wall angle (α) and the original wall thickness (t_0) known as the sine law. [1]

$$\mathbf{t_1 = t_0 \sin (\pi/2 - \alpha)}$$

Allwood et al.[9] examined the deformation mechanism of ISF experimentally through forming specially prepared copper sheets. Strain distributions through the thickness of the sheets are measured The measurements show that the deformation mechanisms of both SPIF and TPIF are stretching and shear in the plane perpendicular to the tool direction, with shear in the plane parallel to the tool direction. Strain components increase on successive laps, and the most significant component of strain is shear parallel to the tool direction.

Mirnia and Dariani[10] used the upper bound approach to study the deformation zone of single point incremental forming of truncated cones. In his research the velocity field and the dissipated power of the process are achieved using an assumed deformation zone and streamlines defined by Bezier curves. The tangential force acting on the tool is attained by optimizing the presented upper-bound solution.

1.2.5 Objective of present work

Incremental forming processes shows a number of advantages as compared to conventional processes but from industries point of view little more research is required to reach their demand effectively. Achievement of these goals will not be possible without better understanding of the process mechanics and influencing parameters.

The power required for forming has application in the designing of tooling and fixtures. Power dissipated in deformation of sheet in SPIF can be obtained experimentally or by analytical ways. Though obtaining power by experiments gives most accurate results but it is required to perform experiments many times with varying parameters. Obtaining power by FEM simulations of SPIF will also give good results but it consumes lot of time.

Hence here the upper bound approach is used to estimate the dissipated power in deformation zone of SPIF in quick way with desired level of accuracy.

Chapter 2

Post processing of FEM results

The aim of the post processing by FEM analysis is to analyze the deformation zone which is used for proposing an expression of velocity field for the Upper Bound Solution of Incremental sheet metal forming. For analyzing the deformation zone, FEA output of single point incremental forming developed by Shibin [14] using ABAQUS, is used for post processing.

Simulation of incremental sheet metal forming processes consists of several steps as follows:

• Building CAD models (blank, tool);

• Generating tool paths for controlling tool movement;

• Building finite element model, applying boundary conditions, defining material properties, contact parameters etc.

• Solving model, post processing.

The sheet metal blank shown in figure 2.1, is of 100x100 and modeled as plane deformable sheet, which is having a similar geometric features as that of the sheet metal in experimental setup. The sheet metal is made up of 4 node quadrilateral shell element with reduced integration. The blank material is taken as homogeneous and isotropic. After this by keeping the clamping fixture of incremental sheet metal forming in experimental setup appropriate boundary condition is provided in FEA model.

Tool of diameter 12.7 unit is modeled as an analytical rigid body with the spherical end. A node is provided at the tool tip which is used to move the tool in specified path. The tool blank interface is considered to be frictionless. Displacement is provided between the tool and the blank. The analysis is assumed to be quasi static type and is done using the standard module on the ABAQUS package.

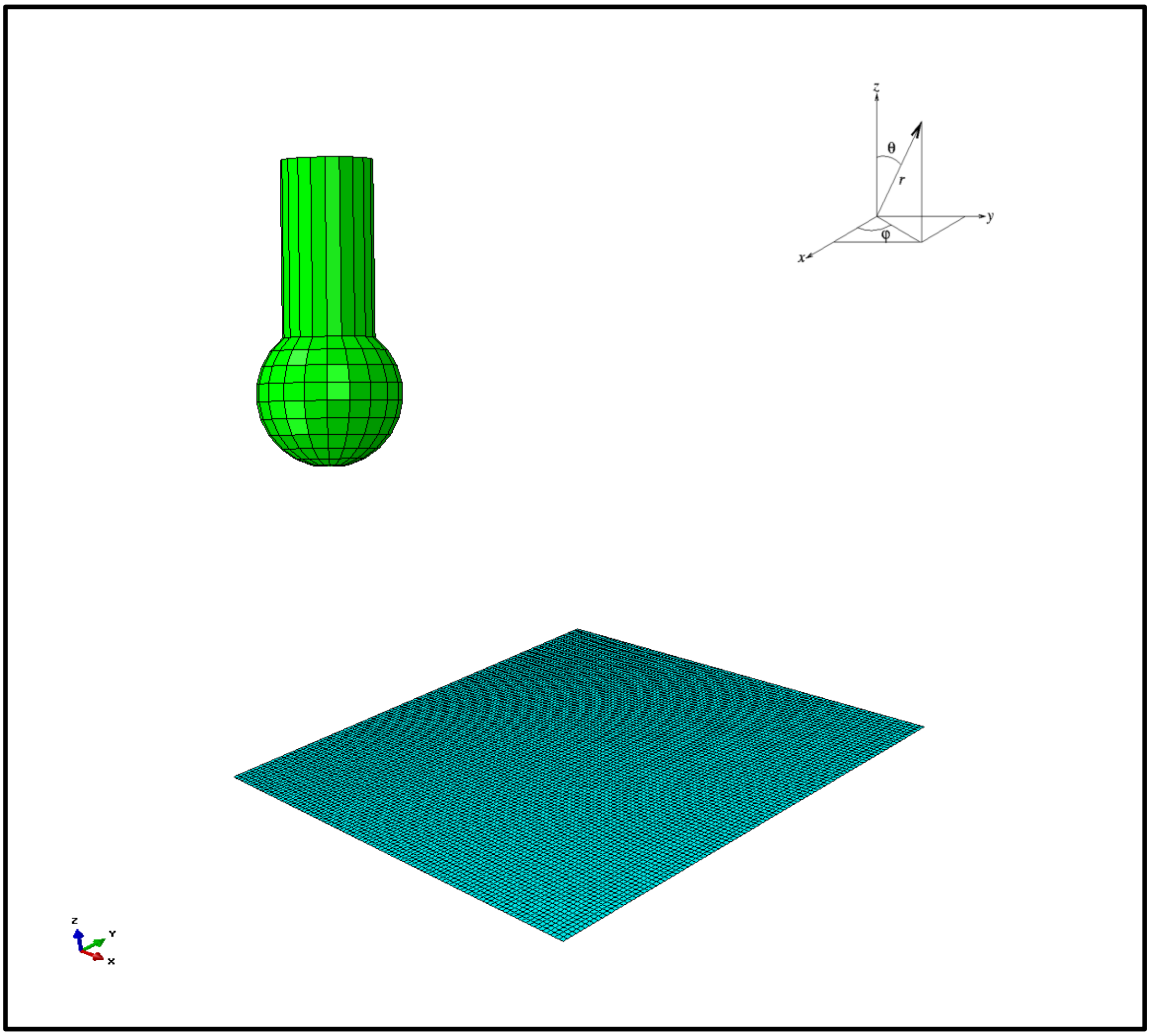


Figure 2.1 Deformable blank and rigid tool in SPIF

For analyzing the deformation zone four different locations are chosen on a meridional line as shown in fig.2.2.

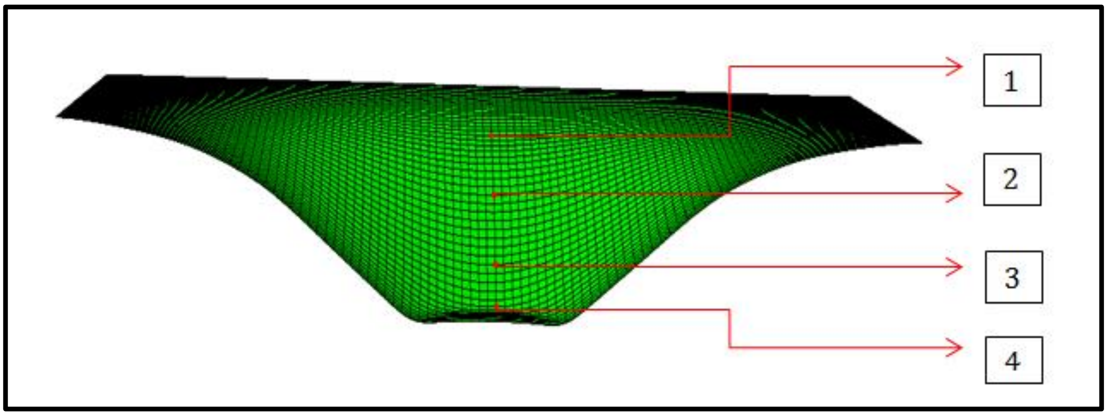
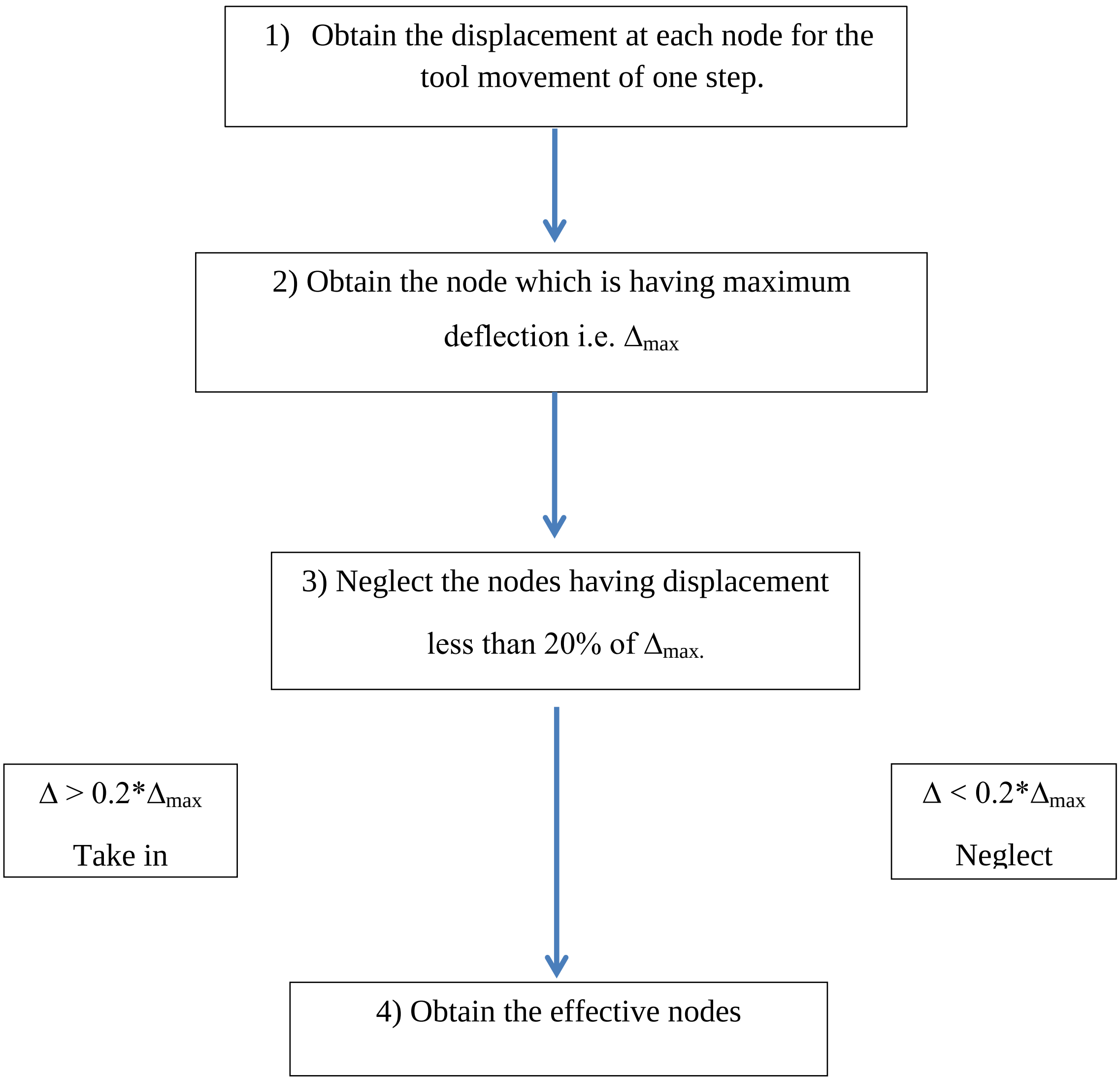


Figure 2.2 four locations on a meridional line chosen for analysis

The above four locations in a meridional line are as follows.

1) Opening region having step frame (572-573)
2) Top wall region with step frame (1632-1633)
3) Bottom wall region with step frame (2698-2699)
4) Base fillet region with step frame (3164-3165)

It is know that in a particular step frame the regions which are near by the tool are having much more displacement as compared to other region. Now for obtaining that particular region one can select only those nodes which are having the displacement more than 20 % of the max displacement. For analyzing the deformation zone one can follow given flowchart.



Above steps are repeated for each locations mentioned above in order to obtain the effective nodes in deformation zone. The each step frame is analyzed and the observation table with figure is shown below.

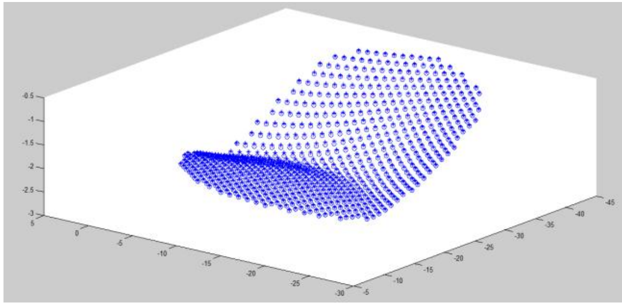
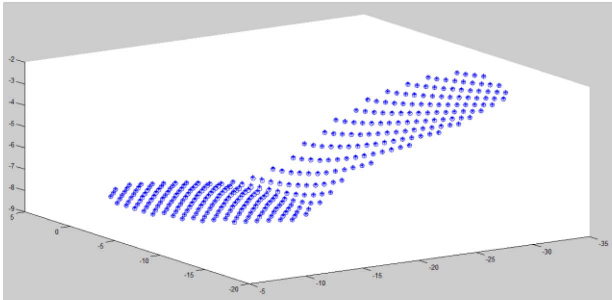
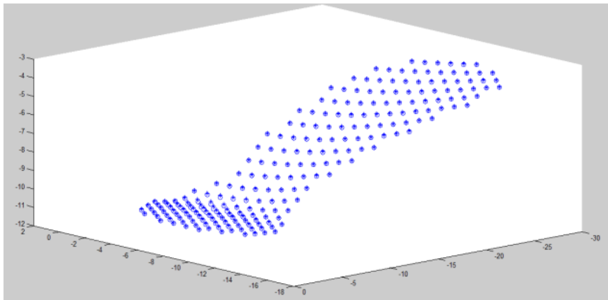
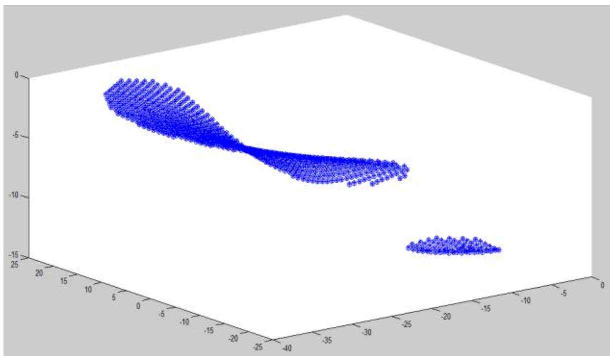
Step Frame	Region	Δ max	No. of effective nodes	Figure showing effective nodes
572-573 (1 in fig. 2.2)	Opening region	0.09963 units	818 nodes	
1632-1633 (2 in fig. 2.2)	Top wall region	0.13052 units	336 nodes	
2698-2699 (3 in fig. 2.2)	Bottom wall region	0.152176 units	224 nodes	
3164-3165 (4 in fig. 2.2)	Base fillet region	0.069216 units	759 nodes	

Figure 2.3: Deformation zone at given step frames

By observing the deformation in these four regions in a meridional line by using ABAQUS post processing, following statement can be made;

- After analyzing different regions on meridional line, it is evident that V_Θ (velocity along the θ direction) is having little effect on deformation zone.
- V_r (velocity in radial direction of spherical tool) is having most influence on deformation zone.
- V_ϕ (velocity along ϕ direction) is having very negligible effect on deformation zone.
- While coming down in wall region it is observed that numbers of effective nodes which are having larger deformation are less.
- But at bottom region suddenly the no. of effective nodes increases. It is because when we are forming in bottom fillet region the displacement will be less.

Chapter 3

Upper bound analysis of SPIF

In the single point incremental forming process the forming forces acting on the tool are in axial, radial, and tangential directions. One can first observed the SPIF process by using FEM analysis through abaqus post processing to analyze the deformation zone which is used for proposing an expression of velocity field for the Upper Bound Solution of Incremental sheet metal forming. Then, the expression for velocity field of the deformation zone is given which can be utilized to calculate the strain rates and dissipated power in the process.

As mentioned in literature that Mirnia and Dariani [10] has made a prior attempt for obtaining the upper bound solution of ISMF process. So before doing work in this area it is required to analyze and reproduce their work. So by analyzing their work following things are estimated.

In their work they considered circular tool path depending upon the amount of incremental depth (Δz) at the end of each path. They first introduce the deformation zone. As shown in figure 3.1 the deformation zone is divided into three regions. Regions I and III are assumed rigid, so that region I was formed in the previous pass and the region III will be formed in the following pass. Thus, region II is formed when the sheet metal approaches the tool. They assumed and optimized certain parameters for predicting the tangential force for incremental sheet metal forming of a cone of AA3003. The parameters are as follows

1) Wall angle (α) = 50^o
2) Tool diameter (dt) = 10 mm
3) Incremental depth = 0.5 mm
5) Yield Strength (K) = 180.39 MPa

(With work hardening law$\sigma_{eq} = K(\varepsilon_o + \varepsilon)^n$)

6) ε_o = 0.00068
7) n = 0.21

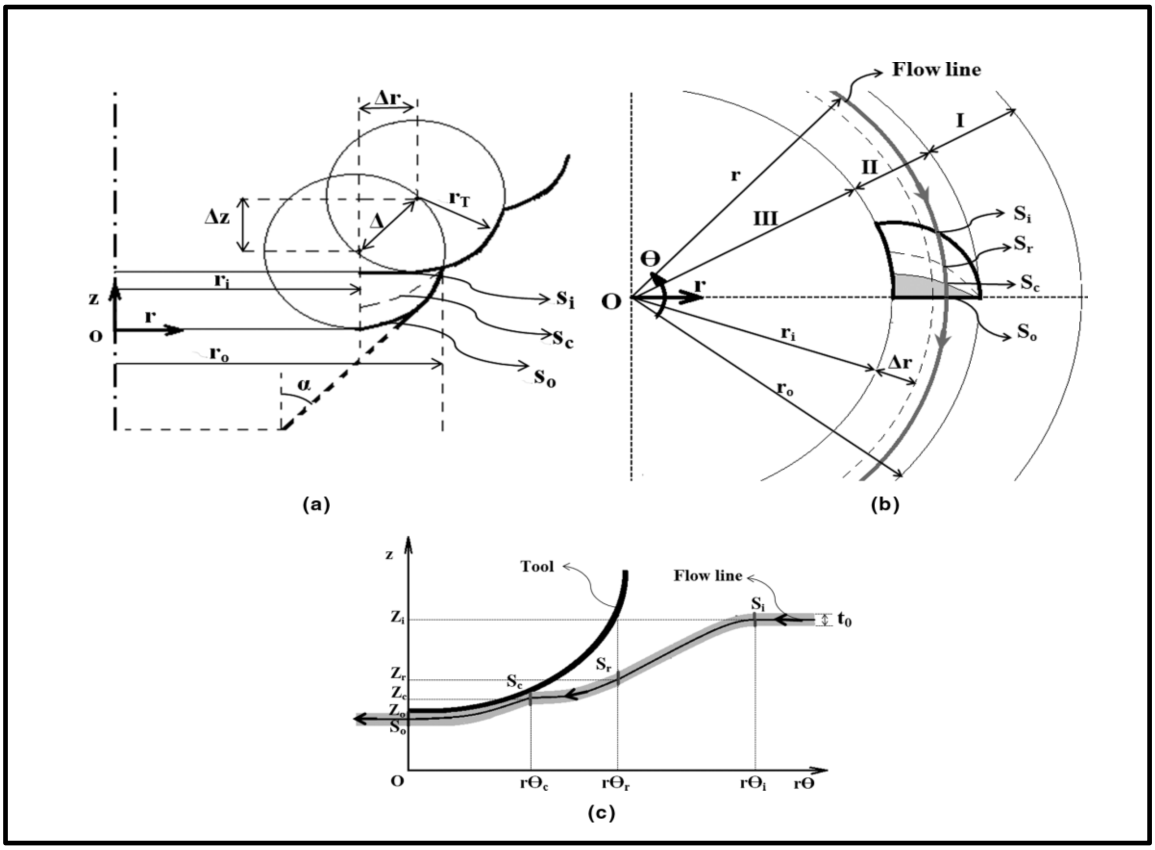


Figure 3.1 Deformation zone of incremental sheet metal forming [9]

By using the above deformation zone expression for velocity field is predicted in r, ϴ and z directions as follows.

1) Ur = 0 { since there is no flow in radial direction}

2) $U_\Theta = r \times \left(\frac{F}{r_i} \right)$

3) $U_z = \left(\frac{F}{r_i} \right) \times \frac{\partial f}{\partial \theta}$

By using the above velocity field strain rate and dissipated power is calculated by using the upper bound analysis approach. In order to reproduce the result the above assumed and optimized parameter and the equations are incorporated in upper bound analysis by using the MATLAB coding. Finally the tangential force required to form the cone is computed.

Now after analyzing their work and observing the deformation zone by post processing of SPIF it feels that the power dissipated in this process can be predicted by upper bound analysis with enhanced level of accuracy. Further upper bound analysis of deformation of sheet with liner interpolation of tool in Cartesian coordinate is done in order to predict the dissipated power in SPIF.

3.1 The deformation zone of SPIF

Figure bellow shows the deformation zone assumed in this research in the different views. The forming tool has a spherical head.

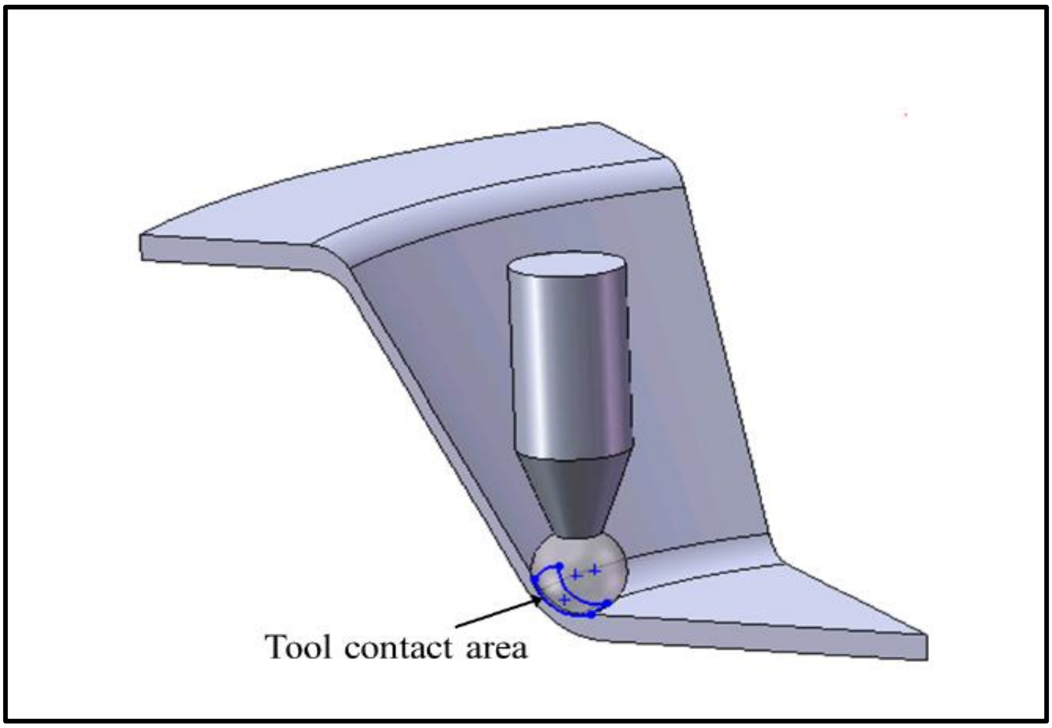


Figure 3.2: Tool contact area [13]

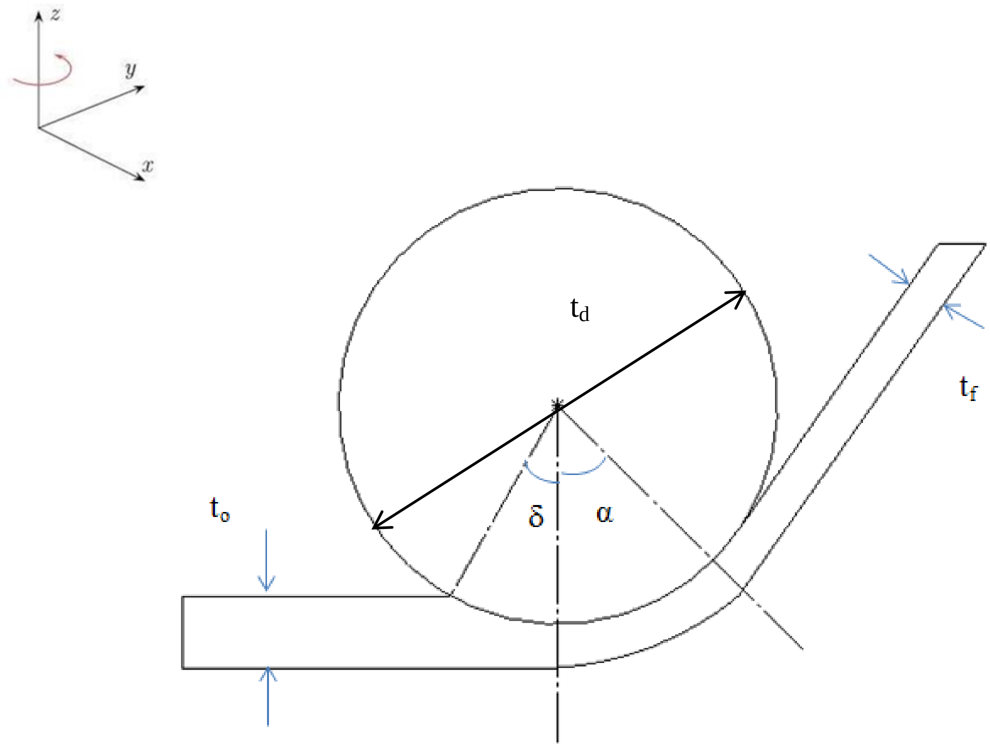


Figure 3.3: Deformation Zone of SPIF

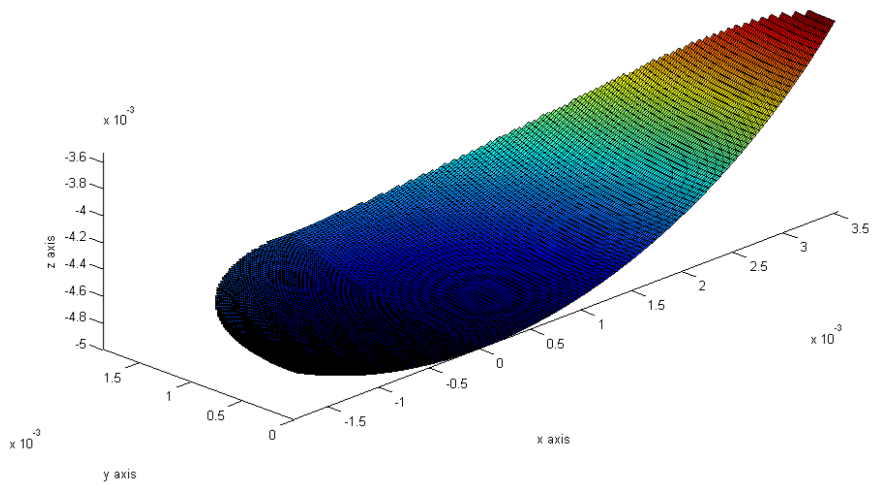
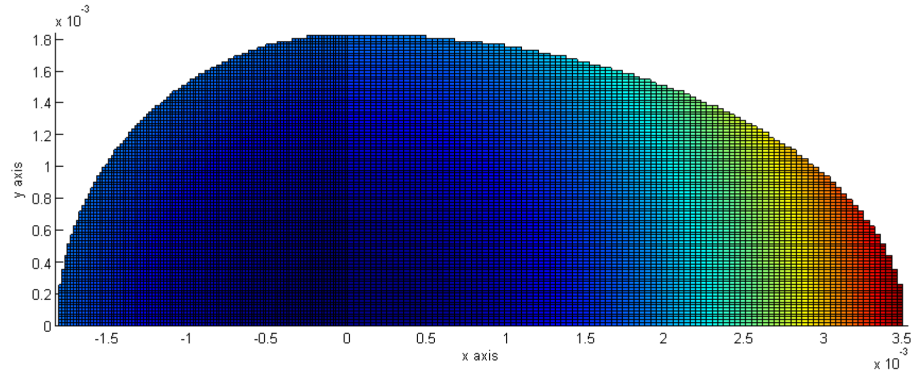
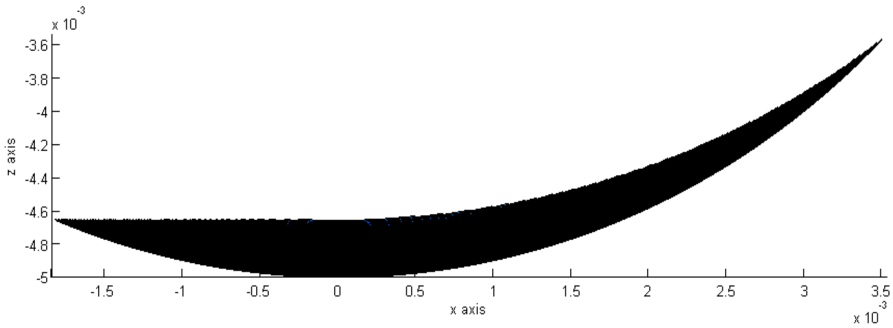


Figure 3.4: Deformation zone predicted using upper-bound for SPIF. Process parameters are

$\alpha = 50^o$, d_t = 10 mm, t_o = 1.2 mm, Δz = 0.5 mm



a)



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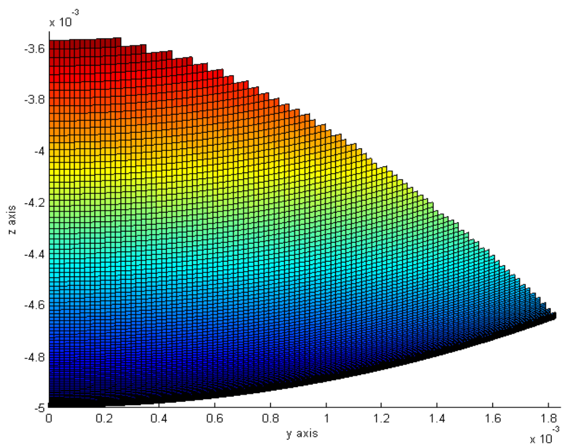

c)

Figure 3.5: Deformation zone relevant to Figure 3.4 in three different views.

Figure 3.3, 3.4, 3.5 shows the deformation zone assumed in front views side view and top view. The forming tool has a spherical head. In figure 3.3 α shows the wall angle and t_o is initial sheet thickness are taken as input parameters. δ is a grove angle which is given by

$$\delta = cos^{-1}\{1 - \frac{(t_o - t_f)}{R}\}$$

Here the plain strain deformation condition is assumed and it is assumed that the part of the sheet which is in contact with the tool is undergoes plastic deformation. Sine law is used for thickness prediction. Hence the shape of the deformation zone is taken from tool geometry. The vertical component of deformed surface (i.e. the contact position of the sheet with tool) is given by

$$z = (R^2 - y^2 - x^2)^{\frac{1}{2}}$$

Now using the deformation zone assumed velocity field can be computed.

3.2 Velocity field of the deformation zone

By analyzing the deformation zone and understanding the physics of ISMF it is evident that there is no flow of material in x direction so

$$V_x = 0$$

If the feed rate of the tool head center is equal to F, then the velocity in direction of y axis will be

$$V_y = F$$

Now velocity in **z** direction can be expressed as

$$V_z = \frac{\partial z}{\partial y} \times F$$

3.3 Strain rates of the deformation zone

The strain rates at deformation zone can be obtained by using velocity field as follows. This can be further used for calculating dissipated power in ISMF.

$$\dot{\varepsilon}_{xx} = 0 \qquad \dot{\varepsilon}_{yy} = 0 \qquad \dot{\varepsilon}_{zz} = 0$$

$$\dot{\varepsilon}_{xy} = \frac{F}{2}\left[\frac{\partial^2 z}{\partial x \partial y}\right] \qquad \dot{\varepsilon}_{yz} = \frac{F}{2} \times \left[\frac{\partial^2 z}{\partial y^2}\right] \qquad \dot{\varepsilon}_{zx} = 0$$

3.4 Power dissipated in SPIF

The dissipated power during SPIF computed using the strain rates can be expressed as

$$\dot{W} = \dot{W}_d + \dot{W}_{sr}$$

Where $\dot{W}_d$ and $\dot{W}_{sr}$ are the dissipated powers in the deformation zone and on the velocity discontinuity surface, respectively.

$\dot{W}_d$ is computed as

$$\dot{W} = \frac{2}{\sqrt{3}} \times yo \iiint \sqrt{\left(\frac{1}{2}\dot{\varepsilon}_{ij} \times \dot{\varepsilon}_{ij}\right)} dv$$

and $\dot{W}_{sr}$ is computed as

$$\dot{W} = \iint k \left|\Delta U\right| ds$$

Chapter 4

Experimental set-up and methodology

4.1 Introduction

Previously all other research published on incremental sheet forming has been developed using conventional CNC machine tools with specially designed spherical tools and appropriate work piece. While use of a CNC machine is attractive because of the low additional costs for beginning operation, it carries some disadvantages: milling machines are generally not designed for high loads normal to the spindle, so there is a danger that the machine will be damaged during incremental sheet forming operations.

Now recently a new dedicated machine is developed at IIT Kanpur for incremental sheet metal forming which is having two spindle heads. In this machine two forming tools can work simultaneously on both side of the sheet independently.

4.2 Machine construction

The dedicated machine is mainly consisting of four units.

1) Upper half
2) Lower half
3) Clamping platform
4) Machine control unit

The dedicated CNC machine for ISMF is consisting of two forming tools; top tool is situated in upper half and bottom tool is situated in lower half. Both tool can move along X, Y, Z axis where X and Y axis is parallel to sheet surface and the Z axis is perpendicular to the sheet surface. Both of the tools can also rotate along Z axis. Clamping platform is where clamping plates of different opening sizes are mounted. Clamping platform is stationary while all the axes movements are given to tools. Machine is controlled by machine control unit which is isolated from the machine and is placed in a separate air-conditioned chamber.

4.3 Forming tools:

Design for fabrication of tool for DSIF is very important. The material usually used for making ISMF tool is hard steel or copper. Following steps is done for fabrication of incremental forming tool.

- EN 32 or copper rod of 25 mm diameter is taken and turned as a cylinder of 15 mm.
- The tip of the rod is turned to required diameter.
- Spherical steel balls are required to drill in such a way that drilled hole matches with dimensions as of the tip of the cylindrical rod.
- The cylindrical rod with tapered tip is inserted in to the drilled hole of the spherical steel ball.
- The tolerance in the hole and the tool tip are such that the ball does not fall of the cylindrical tool and it can be inserted and taken out with little pull or push.
- Spherical balls of various diameters as per the requirement can be used on the tool tip to make the tool of different diameter.

Some of the forming tools used in incremental sheet metal forming is shown in fig. 4.1.

Figure 4.1: Forming tool used in incremental sheet metal forming [15]

4.4 Clamping Plates:

Clamping plates are made up of two mild steel plates as shown in figure 4.2. One of the plate which is kept at bottom is used to support the sheet to be formed and the other plate at the top is used to clamp the sheet. Square opening of different dimensions are machined on clamping plates. Suitable numbers of holes are drilled on the clamping plate so that it can be bolted tightly along with the sheet to be formed. These plates are used to clamp, locate and position the work piece.

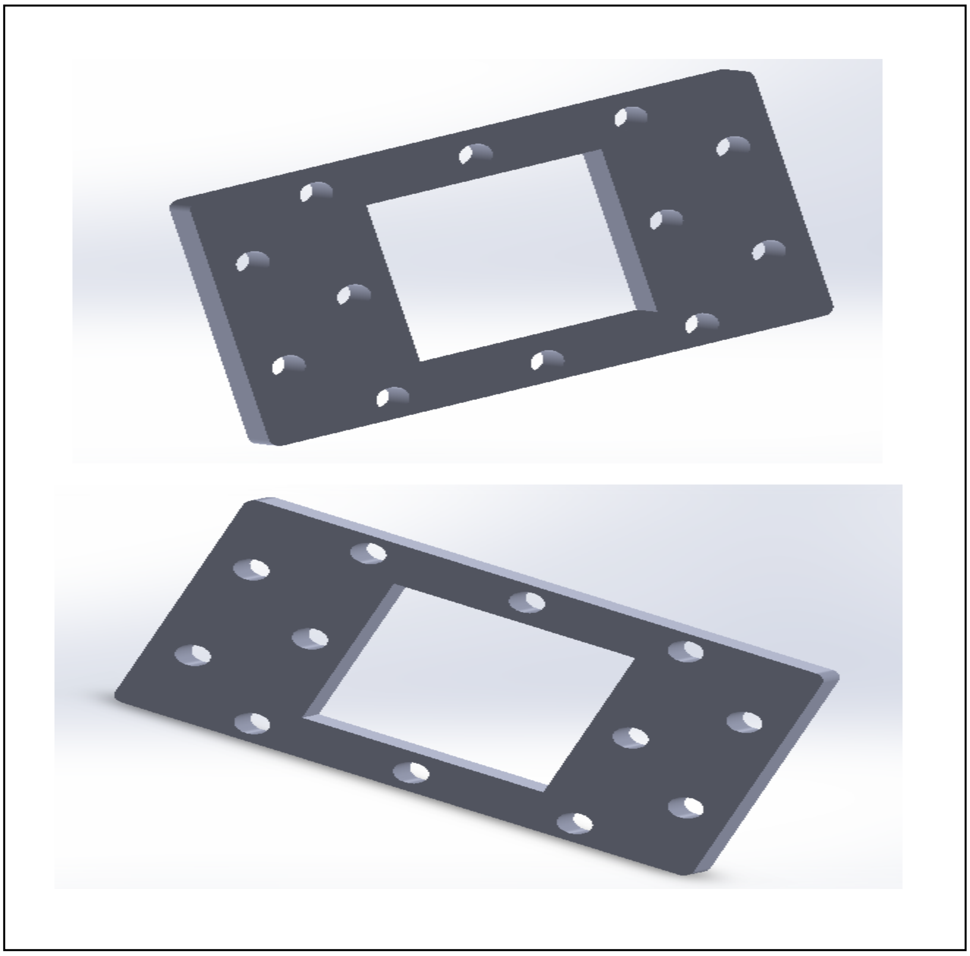

Figure 4.2: Clamping plates used in incremental sheet metal forming

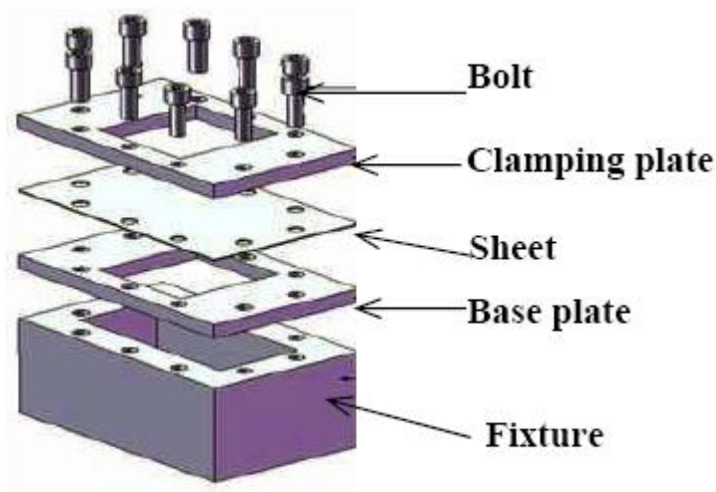

Figure 4.3: Setup used for incremental forming[11]

4.5 Machine specifications

1.	Stroke length	150mm for both the tools in X,Y and Z Directions
2.	Feed	5000 mm/min

Work space

Combined Work space	100mm×100mm×100mm
Work space of top tool	150mm×150mm×150mm
Work space of bottom tool	150mm×150mm×150mm

Motor torque

3 N-m	for X1,Z1,X2,Z2
6 N-m	for Y1, Y2

Table 4.1 Machine specifications.

4.6 Work zero setting

Top tool is brought to the center of the clamped plate to get X1 and Y1 zero and Z1 zero is set by touching the tool tip on the top of sheet. There after removing the sheet, bottom tool is brought below the already set zero of the top tool is in such a way that both tool axis coincides and distance between both tool tips is checked by using a slip gauge. After fine adjustment with the hand wheel this distance is kept below 10μm.

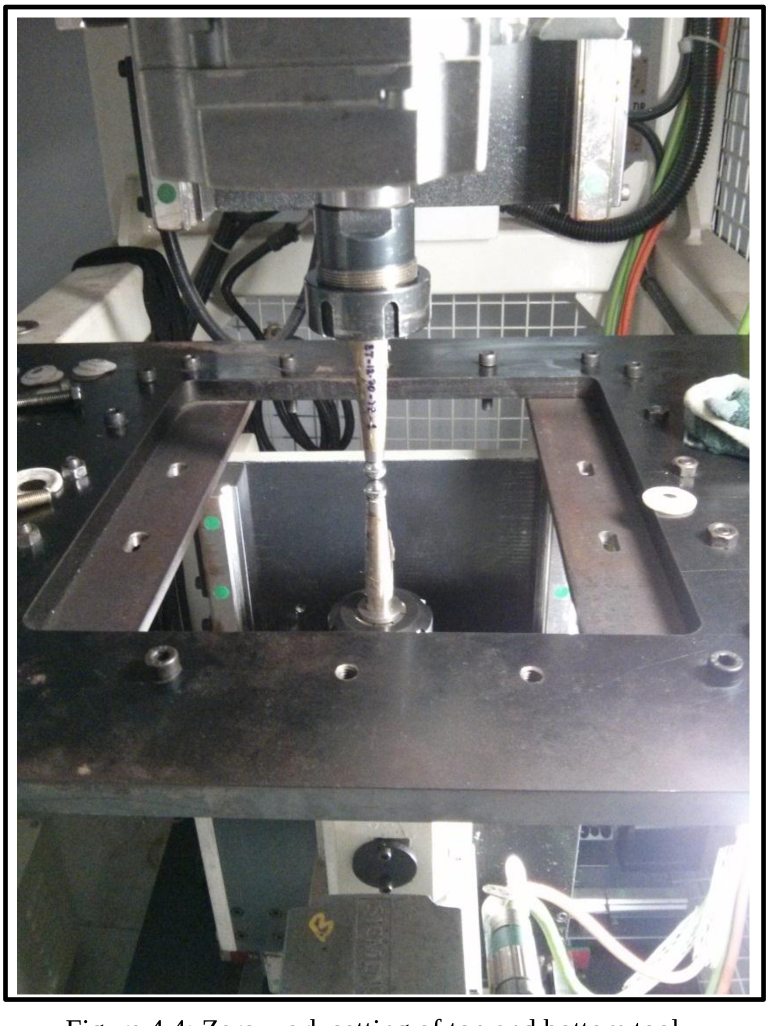

Figure 4.4: Zero work setting of top and bottom tool

4.7 Methodology

1) Generation of CAD model: CAD model of desired component geometry is generated in any CAD package i.e. Pro-E, Solid Works etc. then the CAD model created is saved in STEP format.
2) Tool Path Generation: The CAD model saved in .STEP format is fed into the path generation module developed by Malhotra [16]. By using this module points in a contour of the part geometry is obtained. From the obtained contour spiral path is generated. Then the appropriate tool radius compensation is provided which increases the geometrical accuracy of the component formed.

   For generating tool path two modes of slicing is used

   a) Non adaptive slicing method is used for slicing thickness of 0.1, 0.2 and 0.05 mm respectively.
   b) Adaptive slicing has been used for scallop height of 0.001, 0.002, 0.003, 0.005, 0.0005, and 0.0064 mm.
3) Incremental Forming Using DSIF machine: Experiments are conducted on dedicated DSIF machine. The tool path data is fed into the controller unit which controls the motion of the two spindles independently. The metallic sheet is fixed in clamping fixture. Then according to the tool path given, the two spherical tools deform the sheet incrementally.

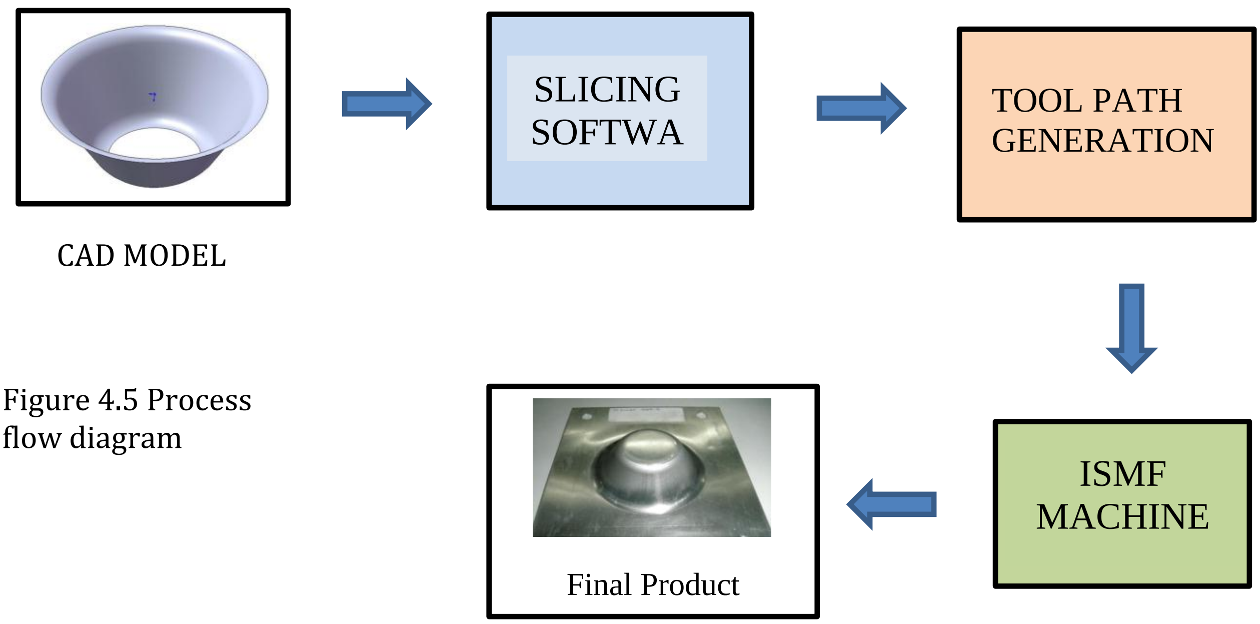

Figure 4.5 Process flow diagram

Chapter 5

Results

On the basis of upper bound analysis of SPIF with the given deformation zone following results are obtained for various combination of parameters. The influence of varying wall angle and tool diameter in dissipated power is observed and plotted. And the trend is compared with experimental results obtained from literature.

5.1 Influence of wall angle

As the part wall becomes steeper, the magnitude of the force needed to form it gradually increases. With wall angles of 30^o, 35^o, 40^o, 45^o, 50^o, 55^o and 60° and the magnitudes of dissipated power are shown in table 5.1 and plotted in Figure 5.1. By increasing the wall angle from 30^o to 60^o it is observed that deformation zone becomes larger and, subsequently, the dissipated power increases.

Process parameters: Tool diameter - 10 mm, sheet thickness - 1.2 mm, step size - 0.5 mm

Wall Angle	30^o	35^o	40^o	45^o	50^o	55^o	60^o
Power Dissipated (watt)	5.24	7.01	9.21	11.58	14.18	17.02	20.09

Table 5.1: Variations of dissipated power with wall angle obtained by presented upper-bound solution.

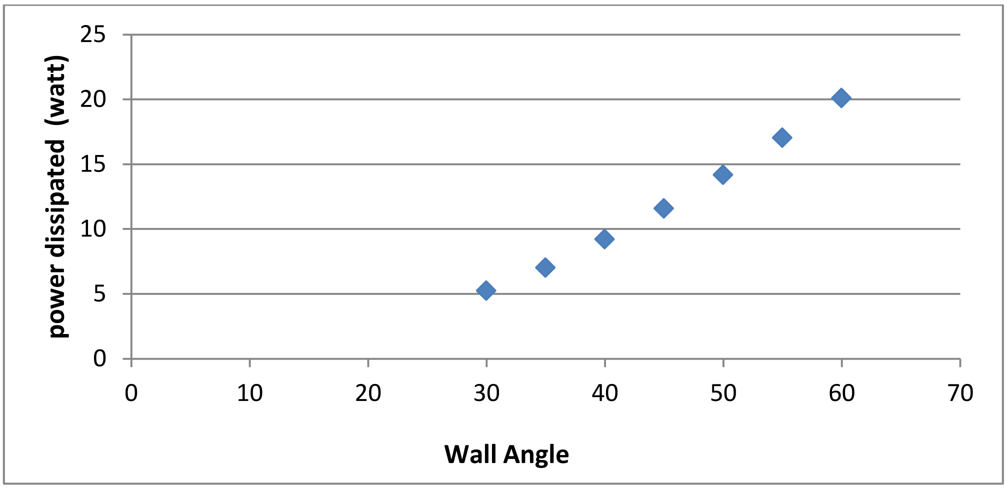

Figure 5.1: Variations of dissipated power with wall angle obtained by presented upper-bound solution. Process parameters are d_t = 10 mm, t_o = 1.2 mm, Δz = 0.5 mm

Now the result for variation of power dissipated with wall angle, obtained from presented upper bound solution is compared with experimental results obtained from literature [12] and shown in figure 5.2 and figure 5.3.

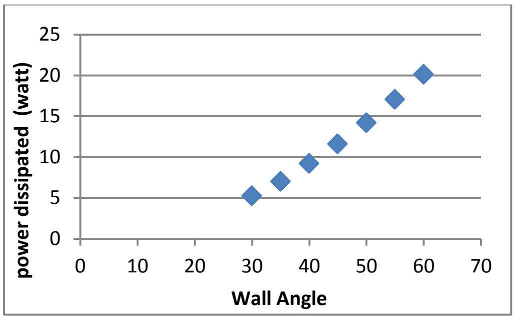

Figure 5.2: Variation of dissipated power with increase in wall angle in presented upper bound solution

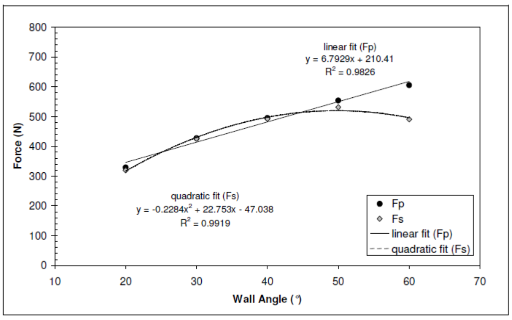

Figure 5.3: Experimental results of variation of forces with increase in wall angle [12]

5.2 Influence of Tool Diameter

Similar to wall angle an increase in tool diameter also causes an increase in the power required for forming. Figure 5.4 shows the dissipated power curve for the 5, 10, 15, 20and 25 mm tool diameters. It is observed that with increase in tool diameter deformation zone become larger so there is increase in dissipated power with increase in tool diameter.

Process parameters: Wall angle - 45^{o}, sheet thickness -1.2 mm, step size - 0.5 mm

Tool Diameter(mm)	5	10	15	20	25
Power Dissipated (watt)	9.6	11.58	13.19	14.57	15.79

Table 5.2: Variations of dissipated power with tool diameter obtained by presented upper-bound solution.

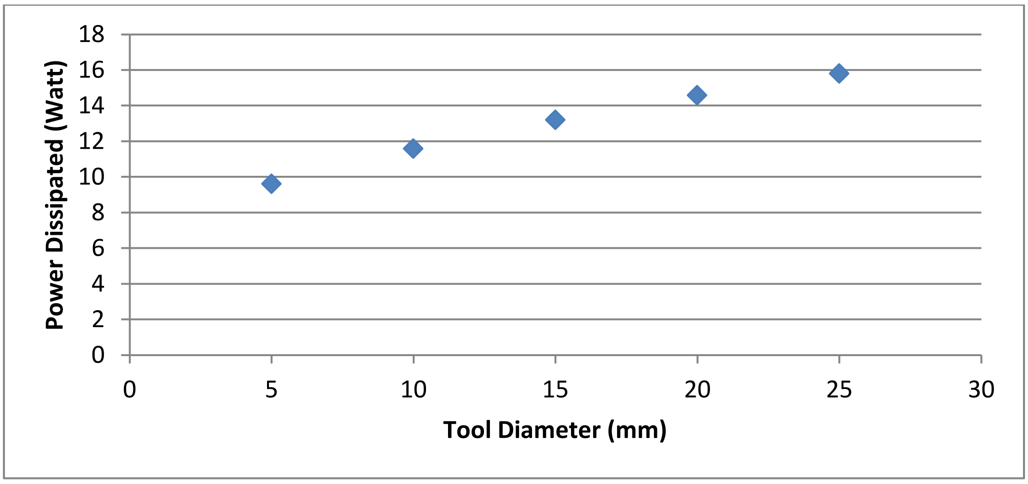

Figure 5.4: Variations of dissipated power with tool diameter obtained by presented upper-bound solution. Process parameters are d_t = 10 mm, t_o = 1.2 mm, Δz = 0.5 mm

Now the result for variation of power dissipated with tool diameter, obtained from presented upper bound solution is compared with experimental results obtained from literature and shown in figure 5.5 and 5.6.

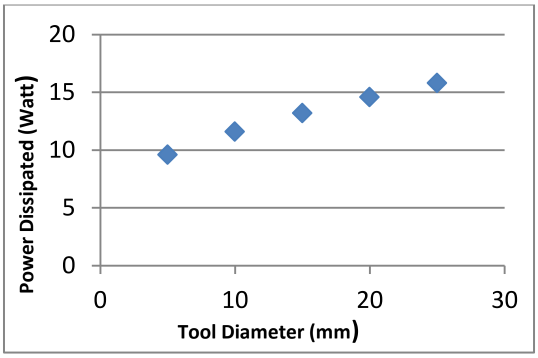

Figure 5.5: Variation of dissipated power with increase in tool diameter in presented upper bound solution.

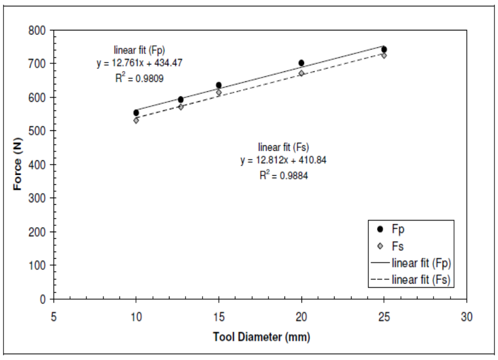

Figure 5.6: experimental results of variation of forces with increase in tool diameter [12]

Chapter 6

Conclusion and future work

6.1 Conclusion

In the present report first the FEM model of single point incremental forming (SPIF) of 30^o cone is used to observe and understand the physics of incremental sheet metal forming. By observing the deformation zone using FEM analysis following conclusions made.

- By analyzing it is evident that U_Θ (velocity along the angular direction in plane perpendicular un-deformed sheet surface) is having little effect on deformation zone.
- U_r (velocity in radial direction of spherical tool) is having most influence on deformation zone.
- U_ϕ (velocity along angular direction of plane parallel to un-deformed sheet surface) is having very negligible effect on deformation zone.

On the basis of above conclusions expression for velocity field is obtained which is further used for computing power dissipated in SPIF process. Further upper bound analysis of deformation of sheet with liner interpolation of tool in Cartesian coordinate is done in order to predict the dissipated power in SPIF.

Dissipated Power predicted in incremental forming can be expected to be similar and repeatable. If the tool diameter or wall angle, are increased the dissipated power will increase as well. An increase of the tool diameter has a substantial impact on the amplitude of power required to form a given
part. Although it can reduce production time by allowing larger vertical step sizes without affecting surface quality, large increases in tool diameter result in much higher forces and could become a limiting factor.

Like tool diameter, wall angle when increased requires much greater forming power. Evidently this is because the deformation zone becomes larger and, subsequently, the dissipated power increases.

6.2 Future work

In future the dissipated power predicted can be utilized to obtain the components of force in three different directions which helps in understanding the process mechanics and influencing parameters. Then the force obtained by dissipated power predicted by upper bound solution can be used for the design of tooling and fixtures.

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Appendix

Components formed by DSIF using Al 5052 sheet

Test	Geometry	Sheet Thickness (mm)	Slicing thickness (mm)
Butterfly shape		1	0.1
		1	0.2
		1	0.05

Test	Geometry	Sheet Thickness (mm)	Slicing thickness (mm)
Pyramidal shape		1	0.1
		1	0.2
		1	0.4

Table 4.2**:** Various components formed in ISMF experiment

Approval Sheet

This thesis entitled "Upper Bound Analysis of Single Point Incremental Forming" by Chhavikant Sahu is approved for the degree of Master of Technology from IIT Hyderabad.

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Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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