# Parts Obtaining Using the Incremental Forming Process

# Parts Obtaining Using the Incremental Forming Process

By

Costel Catalin Coman, Dumitru Nedelcu and Anna Timofiejczuk

**Cambridge Scholars** Publishing

Parts Obtaining Using the Incremental Forming Process

By Costel Catalin Coman, Dumitru Nedelcu and Anna Timofiejczuk

This book first published 2024

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library



ISBN: 978-1-0364-1580-8
ISBN (Ebook): 978-1-0364-1581-5

# CONTENTS

# 1

# STATE OF THE ART ON INCREMENTAL SHEET FORMING TECHNOLOGIES

## Introduction

Cold plastic forming is the method of processing materials in order to achieve a change in the shape and dimensions of the finished part without removing material, as in chipping processes. Conventional cold plastic forming processes produce finished parts for large series and mass production; they provide a high level of productivity, but have the disadvantage of low flexibility and high manufacturing costs in small series production. Due to this drawback, a new flexible process has been developed, namely Incremental Sheet Forming (ISF). This cold plastic forming process is recommended for the production of parts in single, small and medium series production or rapid prototyping. The conventional sheet metal forming process requires special tools with different shapes (punches and dies), simple or complicated, for the progressive production of the finished part, which implies high manufacturing costs. Complex tools are not required for incremental manufacturing; a simple ball-point tool can be used, which is low cost and universal in the sense that it can be used for several categories of parts. Most of the companies involved in the machining of parts have purchased CNC machining centres, taking into account that the development time, i.e. the development costs from the design stage to the actual execution of the parts machined by incremental sheet forming are low compared to the conventional cold plastic deformation forming process when machining a small or medium batch of parts.

This book contains 6 chapters on the research topic of obtaining parts using the incremental sheet forming process. The first chapter deals with the state of the art of incremental sheet forming technologies, where some information on the emergence of incremental sheet forming, an overview of incremental sheet forming technologies, modelling, simulation and optimization of process parameters in incremental sheet forming process, respectively the influence of technological parameters in incremental sheet forming, as well as experimental results on obtaining parts by incremental sheet forming and industrial applications of the incremental sheet forming process are presented. The research objectives and methodology are discussed in the second chapter. Chapter 3 presents the materials, methods and equipment used in incremental sheet forming process. Chapter 4 contains theoretical contributions on the simulation of the incremental forming process using the finite element method, in order to analyse the material behaviour of the part under the action of deformation forces and the distribution of stresses and displacements after the forming passes as well as the wall thickness distribution of the formed part. Chapter 5 deals with experimental contributions on the production of parts by the incremental forming process, where diagrams of the variation of deformation forces, the variation of wall and radius thicknesses during the incremental sheet deformation, the quality of the surface obtained, the influence of technological parameters on the properties of the parts obtained, shape deviations and technological recommendations on the production of parts are presented. Chapter 6 provides final conclusions, personal contributions and future research directions.

## Incremental sheet forming technologies. Definition, classification

Incremental sheet forming is a cold plastic deformation manufacturing process of sheet metal parts characterised by the fact that the local deformation zone propagates successively over the entire surface of the part subject to shape change. To do this, the tool with a hemispherical shape, executes a rotational movement and an advancing movement in the direction of obtaining the cavity of the piece, following a certain trajectory. The workpiece is clamped in a fixture on the machine table. The schematic diagram of the incremental sheet forming process is given in Figure 1.1 [30]. The meanings of the notations in Figure 1.1 are: d - the diameter of forming tool, [mm]; $\alpha$ - the angle of the workpiece wall, [$^{o}$]; h - the height of the workpiece, [mm]; n - the rotational movement of the tool, [rpm]; $\Delta z$ - the displacement of the tool along the Z-axis, [mm]; $\Delta y$ - the displacement of the tool along the Y-axis, [mm].

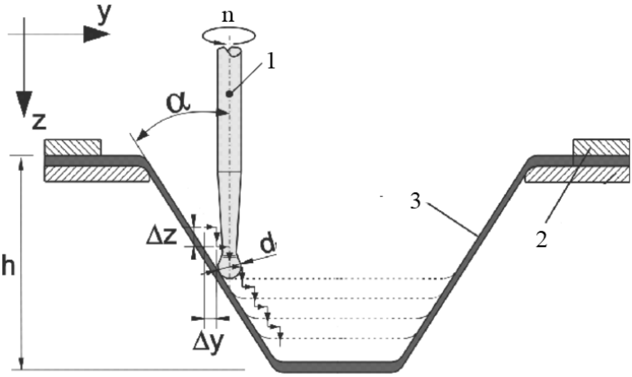



Fig.1.1. Basic principle of the incremental sheet forming process, [30]: 1 – Forming tool; 2 – Clamping device; 3 – Raw material

Initially, the sheet metal blank of a certain thickness has a flat shape. The punch executes a movement along the maximum outer contour of the cavity with depth increment Δz. This is followed by a movement of the tool inwards by the increment Δy, while moving in depth by the increment Δz and making a movement along the contour of the cavity. This sequence of movements of the tool is repeated until the desired height of the part is reached.

The movement of the tool along the path described above is ensured by numerical control equipment. The equipment used for incremental boring can be CNC milling machines, CNC lathes (for hollow turning parts) and industrial robots.

Incremental tooling processes can be classified according to several criteria, including: the shape of the parts being tooling, the number of contact points between the part and the tool, and the number of incremental tooling steps.

They are distinguished by the shape of the incremental backward bulge process:

- Incremental sheet forming with symmetrical shape;
- Incremental sheet forming with non symmetrical shape.

By the number of contact points between the part and the tool:

- Single-point incremental forming;
- Two-point incremental forming, when a support tool (counterform) is also used; this process can be with negative or positive counterform;
- Incremental sheet forming with countertool.

According to the number of forming steps there are:

- Incremental sheet forming with single stage forming ;
- Incremental sheet forming with multi stage forming.

Special incremental sheet forming processhave been developed as follows:

- Incremental hammering;
- Incremental multi-point forming;
- Incremental laser forming;
- Incremental water jet forming;
- Incremental spinning forming.

**Single-point incremental forming**

The blank sheet metal (Figure 1.2) is fixed in the fixture and the tool, with spherical shape, will achievethe desired geometric shape. The tool has a rotational motion and can have a helical trajectory, [8, 16, 28].

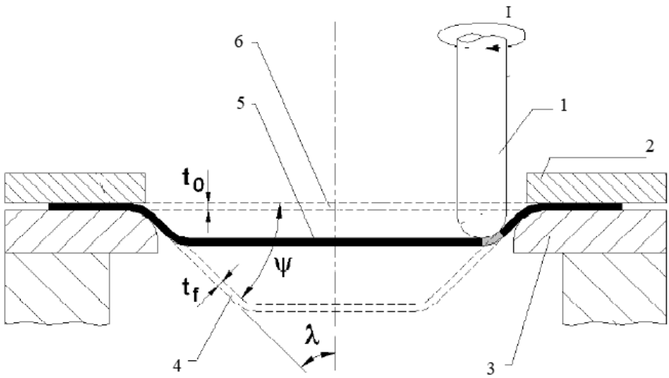



Fig.1.2. Schematic representation of single point incremental sheet forming process, [16]: 1 –Forming Tool; 2 - Clamping plate; 3 - Support plate; 4 - Final part; 5 - Intermediate part shape; 6 – Blank sheet metal; I - rotational movement of the tool

**Two-point incremental sheet metal forming**

In two-point incremental forming, the process is identical to that of single-point incremental forming, except that in addition to the main tool, a counter die is used. The raw material is clamped in the fixture and can be height-adjusted in the Z-axis direction. The tool is similar to the tool in the single-point incremental forming process and performs a geometric up-and-down trajectory. Incremental two-point tooling can be with:

- with spherical tip and partial die (Figure 1.3), [16];
- with spherical tip and full die (Figure 1.4), [16].

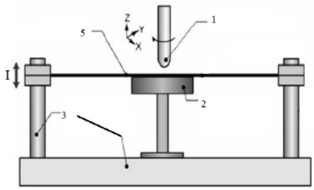


Fig. 1.3. Two-point incremental forming with spherical tip tool and partial die, [16]: 1 - Main tool; 2 - Partial die; 3 - Fixture; 5 – Raw material; I - Tool penetration movement in Z-axis direction

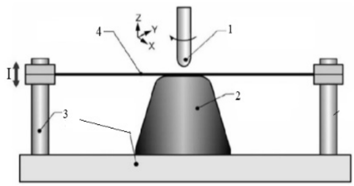


Fig. 1.4. Two-point incremental forming with spherical tip tool and full die, [16]: 1 - Main tool; 2 - Full die; 3 - Fixture; 4- Raw material; 5 – Raw material; I - Tool penetration movement in Z-axis direction

From the point of view of convexity versus form, incremental sheet forming can be :

- negative incremental sheet forming (Figure 1.5a);
- positive incremental sheet forming (Figure 1.5b).

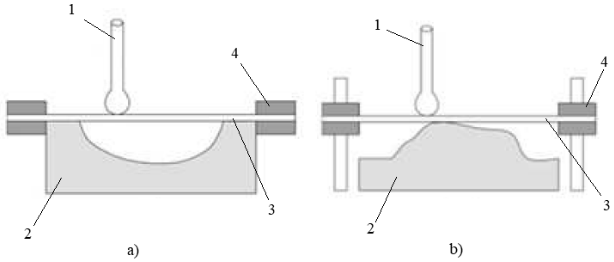



Fig.1.5. Incremental sheet forming, [10]: a) negative incremental sheet forming; b) positive incremental sheet forming; 1 - tool; 2 - counter form (a -negative; b - positive); 2 - negative or positive counter form; 4 - clamping device

**Multistage incremental forming**

In Multistage incremental forming (Figure 1.6), the punch repeatedly (multiple passes) travels across the surface of the workpiece, increasing the wall angle for each pass. From this reason it is important to know the maximum wall angle  for each material with a specific thickness. In order to determine the maximum wall angle, a series of tests are carried out using the tool diameter, the number of passes and the tool path as parameters, [16].

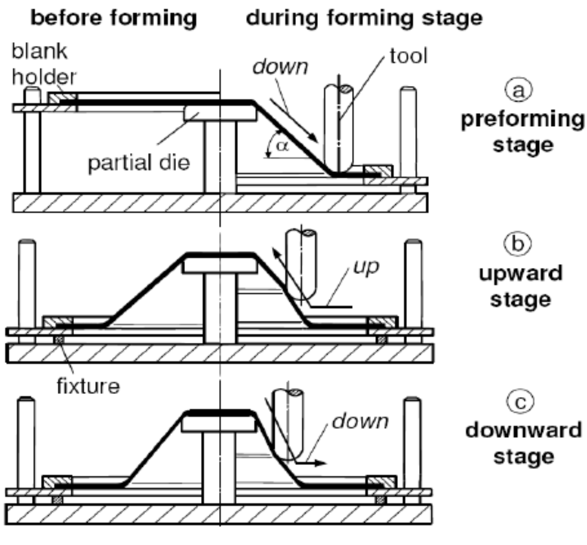



Fig. 1.6. Multistage incremental forming, [13, 16]

## Incremental forming with counter tool

Incremental forming with counter tool (Figure 1.7), is an improved variant of single-point incremental forming, in which a counter tool is used that follows the same trajectory as the main tool, [16].

From this reason, the results obtained with incremental forming with counter tool are considerably better in terms of geometric accuracy and increased plasticity of the part compared to single point incremental forming, [25].

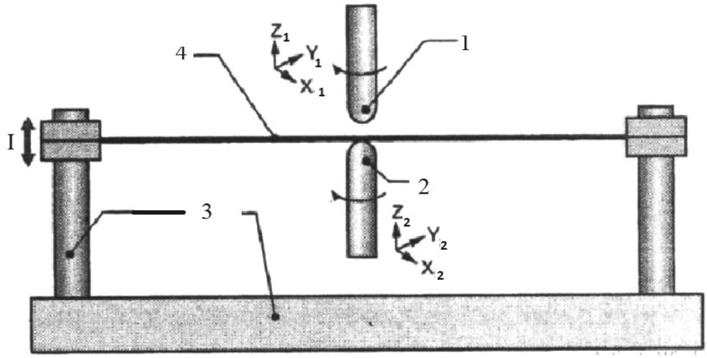



Fig. 1.7. Schematic representation of incremental forming with counter tool, [16]: 1 - Main tool; 2 - Auxiliary tool; 3 – Clamping device;4 – Raw material; I –Forming tool movement in Z-axis direction

## Incremental hammering

One of the earliest incremental forming processes is incremental hammering (Figure 1.8). This process was originally carried out manually, but as technology developed, the process was driven by the use of industrial robots. The advantage of using industrial robots is that the robot arm precisely controls the movement of the tool and the blows applied to the blank. The raw material is clamped in the fixture, where a circular step-by-step downward trajectory will be achieved in each pass, [16].

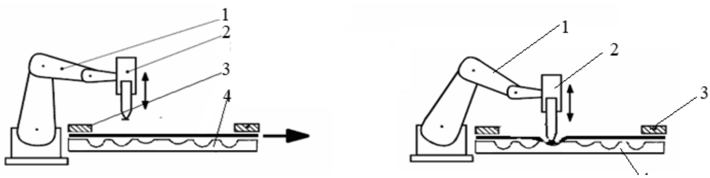



Fig. 1.8. Incremental hammering achieved by an industrial robot, [26]: 1 - Industrial robot; 2 – Tool holder; 3 - Clamping device; 4 - Support frame

**Multi-point forming**

Multi-point forming (Figure 1.9) is a technology similar to the solid die forming process. This process uses two opposing dies pressed into the blank plate to achieve a specific geometry. In multi-point forming, the solid die is replaced by a multi-point die with specific geometries, adjustable in height by means of linear motors, in order to obtain different shapes, [16].

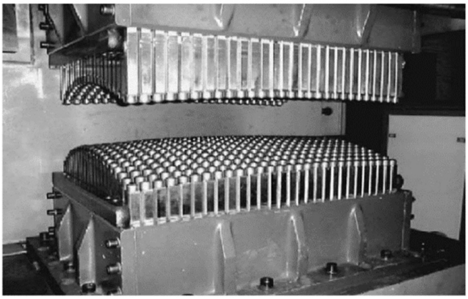


Fig. 1.9. Multi-point bulbing, [16]

**Laser forming process**

The laser forming process (Figure 1.10) is based on thermal stresses induced in the structure of the blank by laser radiation, [16]. The thermal stresses produce plastic deformations resulting in material bending or buckling. This process can be used to repair or modify sheet metal components, [16].

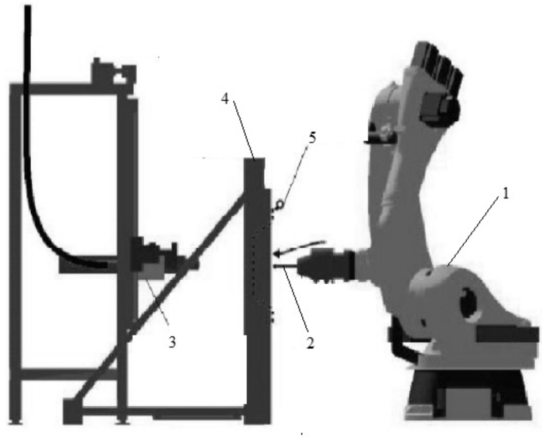



Fig. 1.10. Laser forming, [16]: 1 - 6-axis robot; 2 - Forming tool;
3 - 3-axis laser beam positioning system;
4 – Verticaltable with clamping system; 5 - Coolant circuit

**Water jet forming**

The water jet forming is similar to laser forming, the water jet replacing the laser. The advantages of this process are: flexibility; low equipment costs and low environmental impact.

Among the disadvantages of the process can be listed: low accuracy; high energy consumption; long processing time compared to other incremental sheet forming processes, [16, 27].

**Spinning**

The spinning process is divided into two categories: conventional spinning (Figure 1.11a); Shearspinning (Figure 1.11b).

In conventional spinning (Figure 1.11a), the pieces (3) are formed gradually with a rotating die (1). The die produces local pressure to deform the blank by axial and radial movements on the workpiece surface. The tool can be manually or mechanically operated, production costs for the tool are low, the process is recommended for small series production as it involves several passes, [28]. Shear spinning (Figure 1.11b) is similar to conventional spinning, the difference being the use of the material stretching process compared to conventional spinning where material bending is used. This factor has a major influence on the thickness variation along the wall, [16, 28].

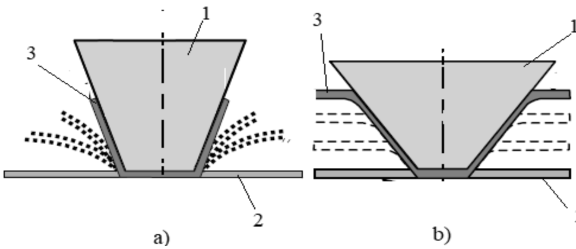



Fig. 1. 11. Variants of the spinning technological process: a) Conventional spinning of a cone; b) Shear spinning of a cone, [28]: 1 - Rotary die; 2 – Raw material; 3 - Final piece

The spinning process is limited by the angle α (Figure 1.12). The final sheet thickness tf is determined by the relationship between the angle α and the initial sheet thickness ti (relation 1.1).

$$t_f = t_i \cdot \sin\alpha, \quad (1.1)$$

where: $t_f$ - final thickness of the sheet, [mm]; α - wall angle, [°]; $t_i$ - initial thickness of the sheet, [mm].

The schematic representation of the sine law, i.e. the deformation of the material upon shear spinning is shown in Figure 1.12, [16].

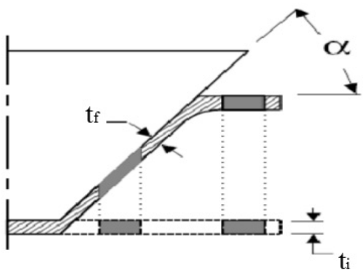



Fig.1.12. Deformation of an element in a shear formed cone, [16]

## Hybrid forming processes

One of the disadvantages of incremental sheet forming process is the excessive time it takes to make a part. An example of a hybrid incremental forming technique (Figure 1.13) is the combination of stretch forming and incremental forming. For each part geometry, different strategies of forming are used, [1, 6].

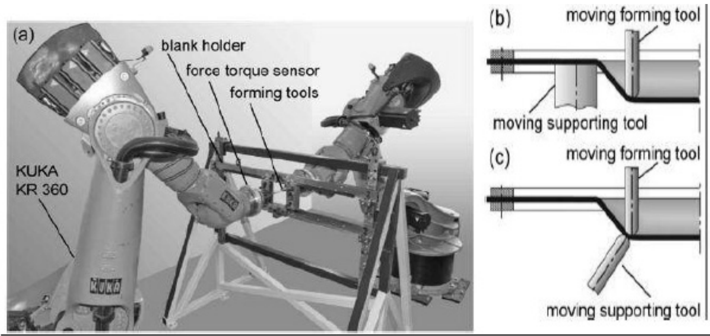



Fig. 1.13. Hybrid forming process, [6]

Figure 1.13 shows a hybrid forming process using two industrial robots, holder tools and sheet metal clamping device. Each industrial robot has force sensors placed on it to measure and maintain the incremental force of the tool during the process. One industrial robot actually executes the incremental forming process and the other is positioned on the opposite side, has the same displacement as the first robot and helps to execute the incremental forming process.

The main features of incremental forming technologies are as follows:

- The incremental forming process does not require a die, but does require a blank clamping system, various tool sizes, forming rollers, active plates, etc.;
- Incremental forming process requires more time compared to conventional forming, but does not require high equipment costs;
- The incremental forming process has a high flexibility, as the same equipment can be used to produce different part geometries;
- The wall angle obtained is larger than with conventional forming; this makes it suitable for processing various materials that are difficult to achieved;

- The spring back effect of the material decreases the accuracy in conventional forming, but using the incremental forming process removes this disadvantage, [30].

## Analysis of the deformation process in incremental sheet forming

The analysis of sheet metal deformation by incremental forming followed:

- determination of the distribution of specific stresses and strains in different areas of the part;
- determination of the forces developed during the incremental forming process;
- determining the maximum wall angle of incremental forming.

**Determination of the distribution of specific stresses and strains in the part**

A study [11] carried out on the incremental forming of 0.4 mm thick sheet metal plates to obtain axial-symmetrical parts of truncated cone shape with forming angles of 30°, 45° and 60°, respectively, followed the distribution of the specific deformations along the radial (φ1), tangential (φ2 ) and axial (φ3 ) directions. Figure 1.14 shows the distribution of the three specific deformations along the part generator. The determination of the specific deformations was carried out by numerical simulation using the LS-DYNA program.

It is found that in the upper part of the cone trunk (where the part flange is), immediately after the connection area, the radial and axial specific deformations are maximum. Tangential specific deformations are negligible with noticeable values in the joint area. All the specific deformations are zero in the areas not in contact with the tool (flange and bottom of the part).

The numerical simulation data were validated experimentally, with a 70-80% agreement between the numerical and experimental results, Figure 1.14, [11].

Similar results of the distributions of the three specific deformations were obtained by numerical simulation and experimentally by incremental forming of a truncated cone-shaped part with a rectangular cross-section. Experimentally, two points were marked on the generating part of the truncated cone, A1 , located towards the bottom of the part, and A2 , towards its flange, whose specific deformations were measured and obtained by numerical simulation, Figure 1.15, [15]. The radial and axial specific deformations have large values, while the tangential ones are not noticeable, Figures 1.16 and 1.17.

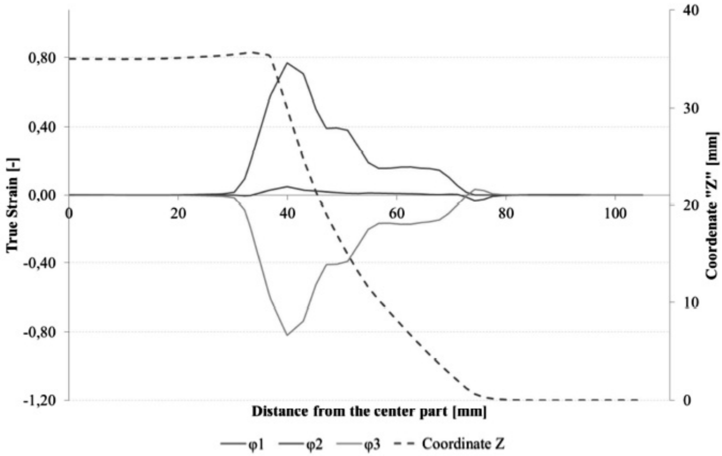



Fig.1.14. Distribution of specific deformations according to part generation, [11]

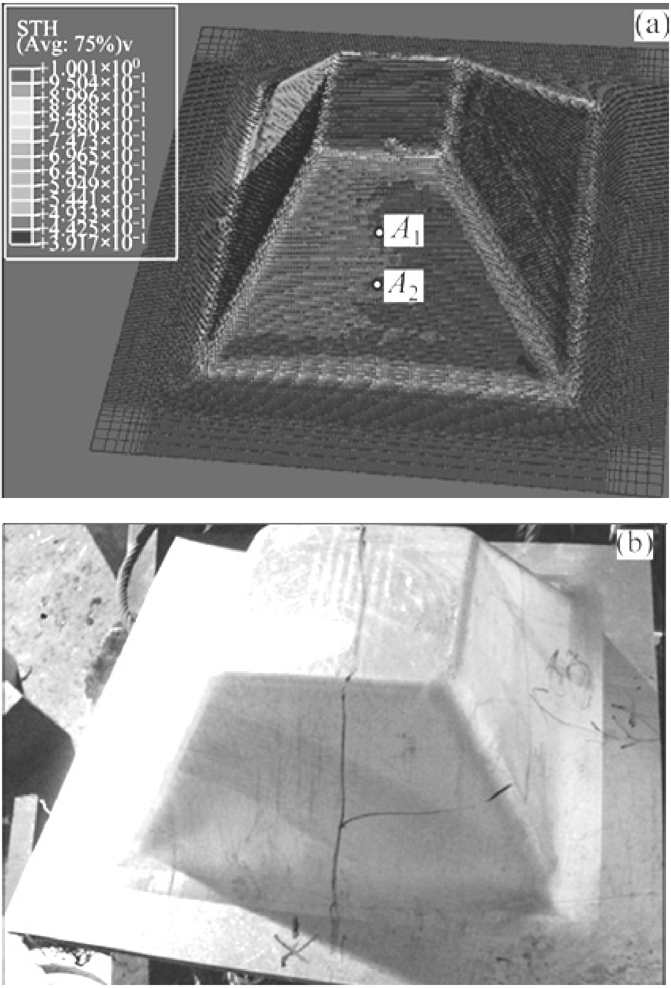



Fig.1.15. Thickness distribution of the part: a) after simulation; b) experimental: A1, A2 - selected nodes, [15]

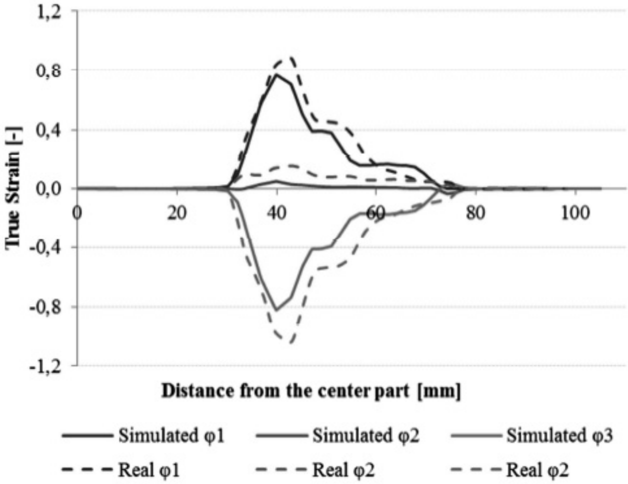



Fig. 1.16. Distribution of the 3 main specific deformations obtained by numerical simulation compared to the deformation obtained experimentally, [11]: 1 - φ1 simulated; 2 - φ1 experimental; 3 - φ2 simulated; 4 - φ2 experimental; 5 - φ3 simulated; 6 - φ3 experimental

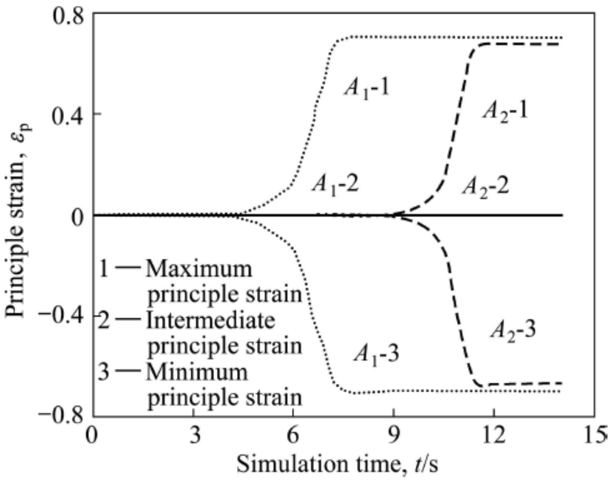
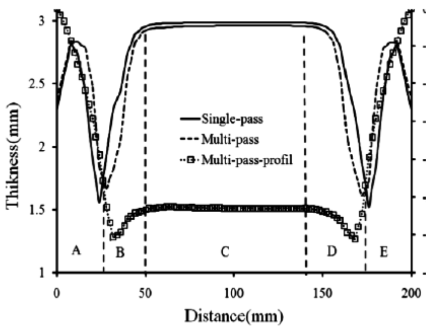


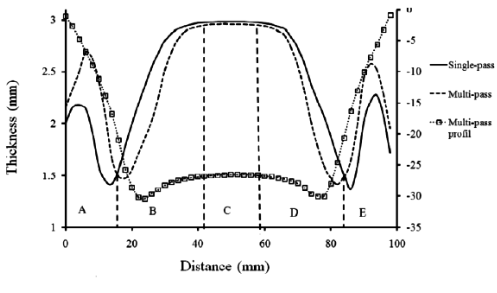

Fig.1.17. Distribution of the three specific deformations in nodes A1 and A2, [15]

In the study [2], the distribution of the equivalent von Mises stress along the generator of a truncated-cone piece with rectangular cross-section was followed. Two incremental forming processes were applied: a) through several passes; b) in a single pass. The tool also followed a trajectory in the transverse direction (across the width of the rectangular section) and in the longitudinal direction, respectively. Figure 1.18 shows the distribution of the equivalent von Mises stress for both incremental forming processes and for the two trajectories followed by the forming tool.

It is observed that the equivalent voltage has the highest values in the area of the radii of the connection between the flange and the hollow surface and has a similar shape. By the multi-pass incremental abutment method the equivalent voltage reaches 230MPa, and by the one-pass method the maximum value is 210MPa.




a)




b)

Fig. 1.18. Distribution of the von Mises equivalent stress in incremental multi-pass and single-pass method for transverse (a) and longitudinal (b) direction, [2]

Similar results were obtained by finite element simulation, Figure 1.19, [2].

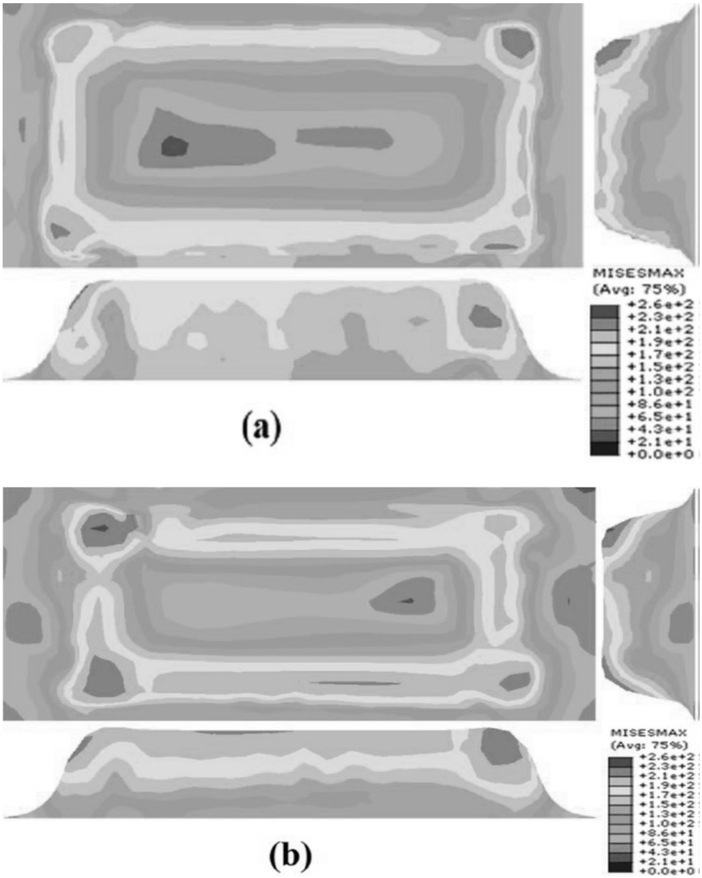



Fig. 1.19. Distribution of the von Mises equivalent voltage in the case of incremental multi-pass (a) and single-pass (b) multi-pass, [2]

**Determination of forces developed during the incremental sheet forming process**

Several concerns have been raised about measuring force and force components in incremental sheet forming.

The forces, during the process of incremental sheet forming, generate two contradictory effects on the material of the piece. On the one hand, they cause thinning of the walls of the part, which leads to a decrease in the thinning, and on the other hand, they cause the material to shrink, which increases the forces.

Figure 1.20 shows the occurrence of bending, stretching and necking stresses after the generation of the part profile as a function of tangential force , [9].

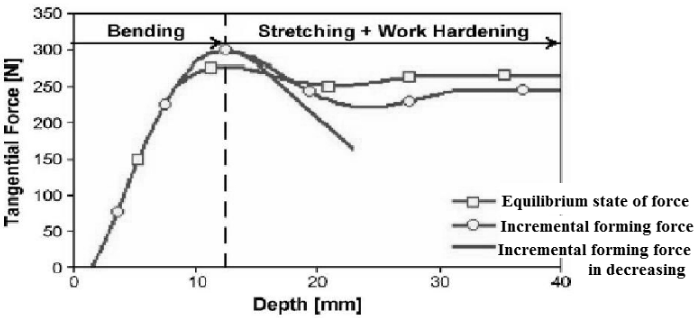


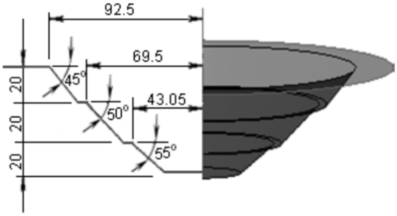

Fig.1.20.Forming forces during the incremental sheet forming process, [9]

These components, in addition to their direct influence on the stresses and strains generated during processing, influence the friction in the blank-stock contact area.

**Determining the maximum wall angle of parts achieved with incremental sheet forming process**

The limits of incremental sheet forming process are defined by the combinations of the maximum deformation of the metal sheets, which can be subjected to different forming conditions such as: stretching, bending. An important factor that must be taken into consideration in the incremental sheet forming process is the forming angle. The forming limit in incremental sheet metal process is maximum forming angle (Φmax), which is the maximum values of the angle of the wall part obtained without cracks on the sheet metal blank. The thickness of the sheet metal blank has an influence on the formability because it affects the maximum forming angle. In other words the large angles on the sheet metal formed part created thinner cross sections and a thinner material is more likely to initiate a crack. The volume constancy leads to a relationship between the wall thickness of part after forming known as the sine law, ( relation 1.1).

The tool used had a hemispherical tip with a diameter of 10 mm and a single tool was used to increase the flexibility of the process. The process parameters used were: feed rate -1000mm/min; tool speed - 1500rot/min; depth - 0.2mm; lubrication with an industrial oil, and spiral tool path. Comparing the two geometries (Figure 1.21, 1.22) of the parts it can be stated that the determination of the wall angle of the incremental sheet forming process is strictly necessary, on which the variation of the part wall thickness depends, [3].



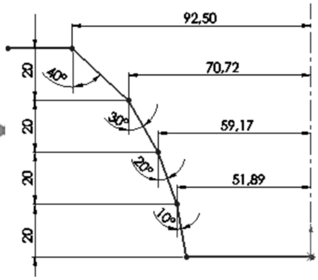




Fig.1.21. Geometry of the first piece, [3]
Fig.1.22. Geometry of the second piece, [3]

If the angle α approaches 0º, there is a possibility of cracking of the part material. When using soft aluminium with an angle α>30º, the part can be achieved without material cracking. Accuracy may be affected when using elastic materials such as stainless steel. The distance between the tool and the fixture can influence the thickness in the sense that if it is too large, the deviation will be too large and if it is too small the material is pressed between the tool and the fixture and thinning can occur, [4].

## Study of the tool path in incremental sheet forming

According to the results in the literature, in incremental sheet forming the tool path was studied for a 2.5 mm forming pitch, where the tool path is stepped (Figure 1.23), and 3 mm, where the tool path is helical, respectively (Figure 1.24).

The first movement of the tool is in the horizontal plane (XY), then the movement is made in the vertical plane, in the direction of the Z axis. Figure 1.25 shows the contour path where the tool moves only along the contour of the workpiece. The "pocket" trajectory at which the movements of the tool in the workpiece are as if it has been milled out of a whole material, (figure 1.26), [14]. The forming depth has a great influence on the accuracy of the final workpiece, by increasing it there is a decrease in the plasticity of the material and the quality of the machined surface. Tool paths can be one-way (Figure 1.27a), in alternate directions (Figure 1.27b) and spiral paths (Figure 1.27c).

Before starting the incremental forming process it is necessary to set the correct trajectory to get the desired piece. The steps to be followed are shown in Figure 1.28, [13].

Fig.1.23. Tool path with 2.5 mm stepped pitch, [14]

Fig.1.24. Trajectory of the 3 mm helical pitch tool, [14]

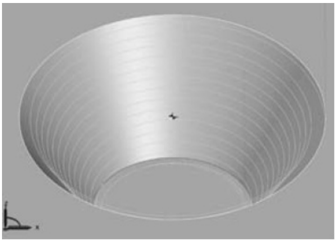


Fig.1.25. Contour trajectory, [14]

Fig.1.26. The 'pocket' trajectory, [14]

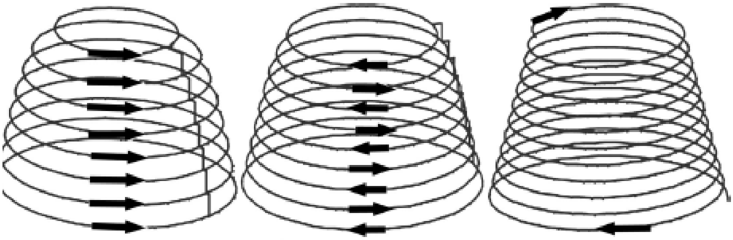


Fig.1.27. Types of tool paths, [15]

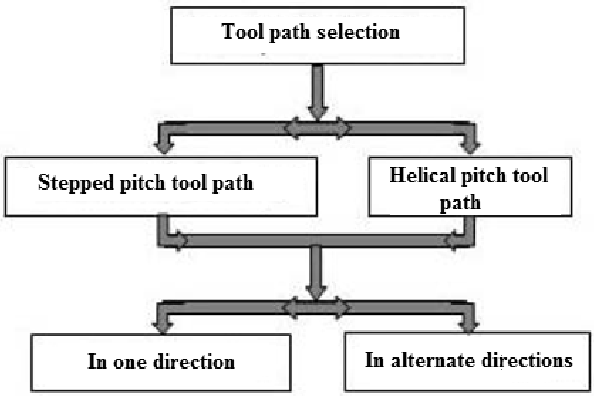



Fig.1.28. Setting the tool path for single point incremental sheet forming, [13]

For incremental forming of complex workpieces machined in a single pass, there are two tool movement options:

a) by contour contour lines describing the outer contour of the part offset on the Z-axis for each penetration depth of the well (Figure 1.29);

b) the trajectory composed of the archimedean spiral and the contour line offset on the Z-axis for each penetration depth of the well (Figure 1.30), [20].

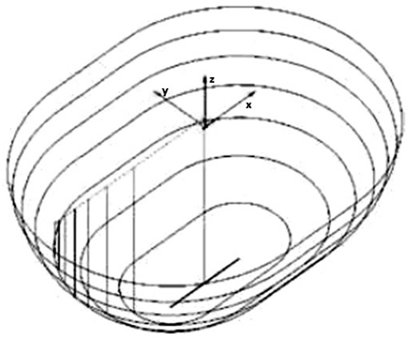



Fig.1.29. Contour contours offset on the Z-axis, [20]

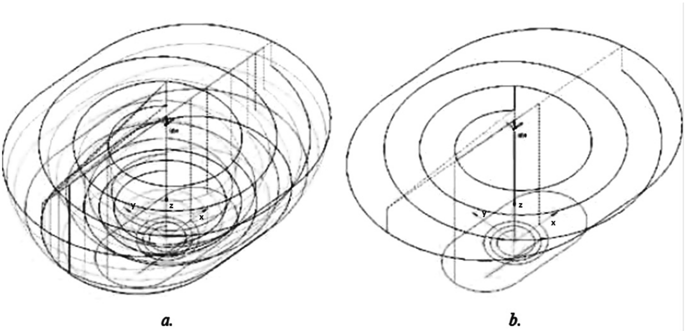



Fig.1.30. Trajectories composed of spiral arcs and offset contour contours on the Z axis, [20]

The problem with incremental forming of complex parts is the development of cracks due to the application of repeated stresses to the material in the transition zones from spherical to flat surface. For this reason, experimental research on incremental forming of complex parts has focused on optimising tool displacement. Thus, the deformation behaviour of bimetallic sheet has been studied under the lowest possible shape deviations, without dangerous material thinning, [20].

Thus, the machining of the workpiece was carried out in two stages, [20]: roughing, which deforms the workpiece to a dimension 2 mm less than the final dimension of the workpiece, and flat finishing, which deforms the workpiece to the final dimension.

The flat finishing stage is achieved by the following methods:

- finishing made in a single pass, with trajectories inclined at different angles to the X-axis;
- plane finish, trajectories oriented at an angle of 0º to the X-axis (Figure 1.31);
- flat finishing, trajectories oriented at a 90º angle to the X-axis (Figure 1.32);
- flat finishing, trajectories oriented at an angle of 45º to the X-axis (Figure 1.33).

The paths for making the final part by roughing and planar finishing forming in one pass are shown in Figure 1.34, [20].

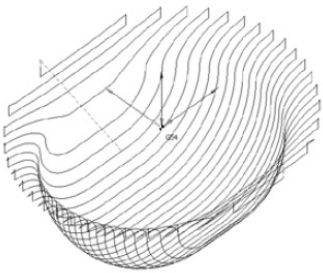


Fig.1.31. Planar finish made in a single pass - 0° oriented trajectories, [20]

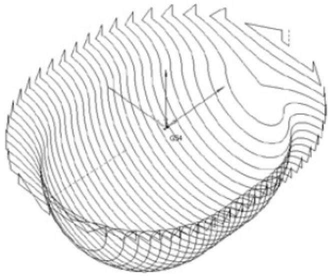


Fig.1.32. Planar finish made in one pass - 90° oriented trajectories, [20]

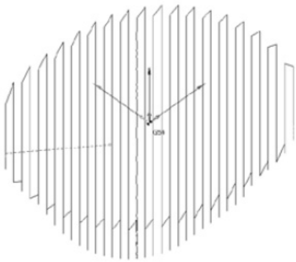


Fig.1.33. Planar finish made in a single pass - 45° oriented trajectories, [20]

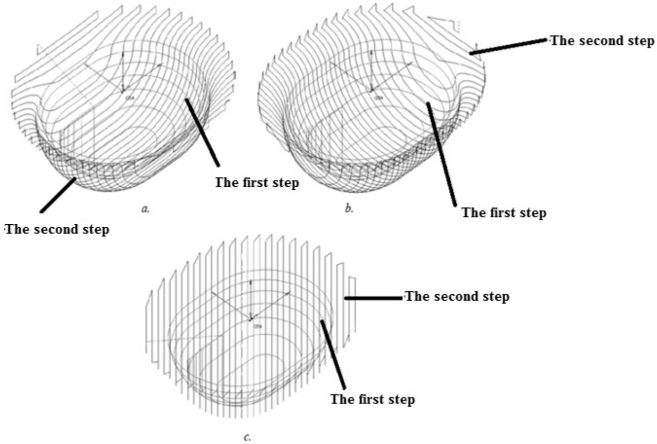



Fig.1.34. The paths of the final part, [20]

**Influence of tool diameter and corner radii on the parts accuracy achieved by incremental sheet forming process**

In order to determine the influence of tool diameter and radii at the corners, different parts with different geometries were made (Figure 1.35), [16].

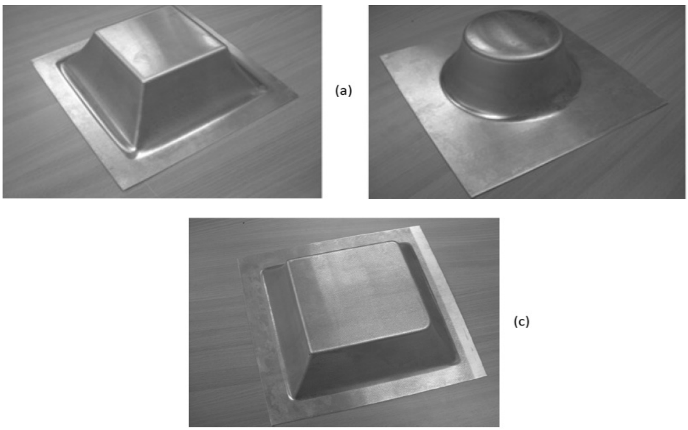



Fig.1.35. Incremental forming parts from a single pass at different angles, [16]