"LUCIAN BLAGA" **UNIVERSITY OF SIBIU**

FACULTY OF ENGINEERING

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DOCTORAL THESIS - *abstract*

Contributions to the incremental forming of thin metal sheets

Doctoral advisor: Prof. Dr. Eng. Octavian Bologa

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Faculty of Engineering

Doctoral thesis

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Sibiu, 2011

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1 INTRODUCTION

In the last few years, the metal forming industry has seen the arrival of flexible manufacturing, the production adapting to the more and more diversified requirements of the consumers. The processes by which parts are realised through metal forming are, generally, the drawing, deep drawing, moulding or hydroforming, which allow the manufacturing of parts in large batches or as mass production. However, these processes are costly, since it is necessary to manufacture tools that follow the shape of the part that needs to be realised and for the manufacturing of a new product it is necessary to realise a new set of active tools.

More recently, new metal forming processes have appeared, such as the incremental forming processes, which eliminate this limitation. In order to realise parts using this process, it is not necessary to have costly active tools, while for realising a new product it is necessary to change only the equipment's CNC software programme, for example for the incremental forming of metal sheets on milling machines, this being a very flexible forming process. At the same time, given the fact that the forming tool moves along a predefined contour, the forming time is much longer than in the case of classical forming processes. Due to this long forming time, but also due to the high flexibility degree, this forming process is suitable for the manufacturing of parts in small batches, for the manufacturing of unique parts or for rapid prototyping.

1.1 Motivation of the unfolded researches in the context of the tackled topic

The incremental forming procedure of metal sheets is a modern method for metal forming, with an enormous potential concerning the flexibility degree and the personalisation of parts obtained through this process.

Within the analysed process, the forming is carried out with the help of a numerical controlled punch. This follows a trajectory defined by the CNC software of the NC machine on which the processing is done. The material is formed partly, only in the area which gets into contact with the punch, hence the name of incremental metal forming, the material being formed gradually.

Although the researches in this domain are more and more numerous, there have not yet been studied elements such as the distribution of strains in the part, the manner in which they vary according to the geometry of the formed part, the manner in which their distribution influences the forming strategy, but also how several parameters influence the process.

The researches carried out within the thesis aim at determing the strains on parts obtained following the unfolding of a "single point" incremental forming process. During the researches, there have been determined the influence of geometrical parameters (punch diameter, size of the vertical pitch, inclination angle of the part's walls etc.) on the values of the strains, the influence of the forming manner on the strains suffered by the blank for obtaining the same part. The researches were carried out using various types of trajectories: trajectory for obtaining a straight groove, for obtaining a cone frustum, a pyramid frustum or a dome. At the same time with determining the strains, there have been also determined the forces within the studied metal forming process.

1.2 Evolution and structure of the thesis

The topic of the doctoral thesis is circumscribed to the preoccupations of the team of the Research Centre for Metal Forming from the „Lucian Blaga” University of Sibiu and was tackled in order to study some aspects related to the incremental forming of metal sheets.

The formulation of the present thesis' objectives was based on the conclusions drawn from the analysis and synthesis of the state of the art of researches in the domain of incremental forming of metal sheets.

The thesis comprises six chapters in which there are presented aspects regarding: the state of the art of researches in the domain of incremental forming of metal sheets, theoretical determinations of the influence of process parameters on the strains and forces at the incremental forming, simulation through the finite elements method of the behaviour of metal sheets during forming, experimental installations used for realising the experiments, experimental researches for determining the mechanical characteristics of the analysed sheets, determining the distribution of strains for various tool trajectories and the influence of geometrical parameters on these distributions, determining the forces and the influence of parameters on them, determining the influence of certain parameters on the geometrical precision.

At the end of the thesis there are presented, in a synthetic manner, the conclusions and personal contributions with regard to the unfolded researches and there is realised also a global assessment of the topic studied throughout the thesis, emphasising the possibilities for its future development.

For the competent advishorship, the trust and the support received throughout the duration of preparing the doctoral thesis, the author wishes to express the most sincere thanks and gratitude towards his scientific advisor, Prof. Dr. Eng. Octavian Bologa.

Over this whole period, the author benefitted from the support, guidance or understanding of several people whose actions made it possible to unfold and finish his researches. Therefore, here too, the author extends sincere thanks and expresses his gratitude especially towards the colleagues from the collective Machines and Equipment, towards the colleagues from the collective BPM, the colleagues from the collective TCM, as well as towards other colleagues from the Faculty of Engineering who helped him during the preparation of the thesis with pertinent advice, with critical analyses of the unfolded research stages and/or with research-specific software and equipment.

Also, for facilitating the unfolding of the research practice stage at the Institut für Umformtechnik (IFU), University of Stuttgart - Germany, as well as for the whole support and goodwill shown for the duration of this stage, the author wishes to thank warmly Prof. Dr. Eng. Matthias Liewald and Dr. Eng. Stefan Wagner from IFU.

Furthermore, the author wishes to thank the members of the Doctorate Commission for their contribution in the finishing stage of the thesis and for its assessment.

The appreciation and gratitude the author wishes to express towards his family, for all the understanding and moral support that they have shown in all these years, when professional matters had to come first, are beyond any words.

2 STATE OF THE ART REGARDING THE INCREMENTAL FORMING OF METAL SHEETS

2.1 Definition of the process

The term incremental forming describes a wide family of forming processes, all of them characterised by the fact that at any moment, only a small part of the blank is formed, while the formed area moves along a predetermined trajectory of the forming tool. The blank is fastened in a device called in this thesis „blankholding system”. The forming can be done with one or two active elements. The active element that produces the deformation directly is called "active forming element". The active element that contributes partly or totally to realising the part's shape is designated as „active support element”.

This category can comprise both a part of the classical forming processes as well as other procedures that appeared more recently.

The main characteristics of the incremental forming process are:

- the process does not require a die in the classical sense, but rather only a blankholding system and active forming elements that can be, from case to case, small size punches, forming rolls, pins, active plates etc.;
- the process is used as an alternative to classical processes in the case of manufacturing parts in small batches or as prototypes;
- the incremental forming process is slow compared to conventional pressing processes, but does not require expensive processing equipment;
- the manufacturing time of the parts depends on the length of the forming trajectory needed for realising the required profile, on the speed of the active element which realises the forming and on the available power at the employed equipment;
- the forming method has a high flexibility, the same equipment allowing the manufacturing of various part geometries and sizes;

- the forming being localised, there remain unformed, plain ares, while in the formed areas there can be noticed a significant thinning of the material's thickness;
- the forming degrees obtained with this process are much higher than those obtained through conventional pressing processes, this rendering the procedure suitable for the processing of materials that are difficult to process by forming;
- the forming being asymmetrical, the stresses and strains states in the material are uneven, which leads to considerable springbacks in the material, so that the dimensional precision is smalled than in the case of a conventional pressing process, while the methods for removing this disadvantage are still under research.

2.2 Classification of incremental forming processes

The bibliographical research that was carried out has revealed the existence of a large diversity of processing methods, but no classification was found that would include all these processes.

The classification of these processes can be done taking into account several criteria.

A first classification can be done according to the type of the employed blank. Thus, the processes can be separated into two main groups:

- incremental forming of volumic (massive) blanks;
- incremental forming of sheet-type blanks.

The first category includes orbital forging, roll forming, incremental forming with rolls in planetary motion etc.

Taking into account the topic of this thesis, the classification of the incremental forming processes will be detailed, in the following, only for the case of processing sheet-type blanks.

According to the active forming element, the processes can be:

- with punch;
- with a roll/rolls;
- with water jet;
- with laser;
- with a ball beam.

Function of the forming type, the processing can be:

- free (without an active support element);
- with an active support element such as:
  - counterpunch;
  - roll;
  - pin;
  - active plate with part or full surface.

The application manner of the forces can be:

- continuous;
- intermittent.

The process can use a blankholding system that is:

- fixed;
- mobile.

According to the processing temperature, there can be:

- hot forming;
- cold forming.

A synthetic classification of these processes is presented in figure 2.1.

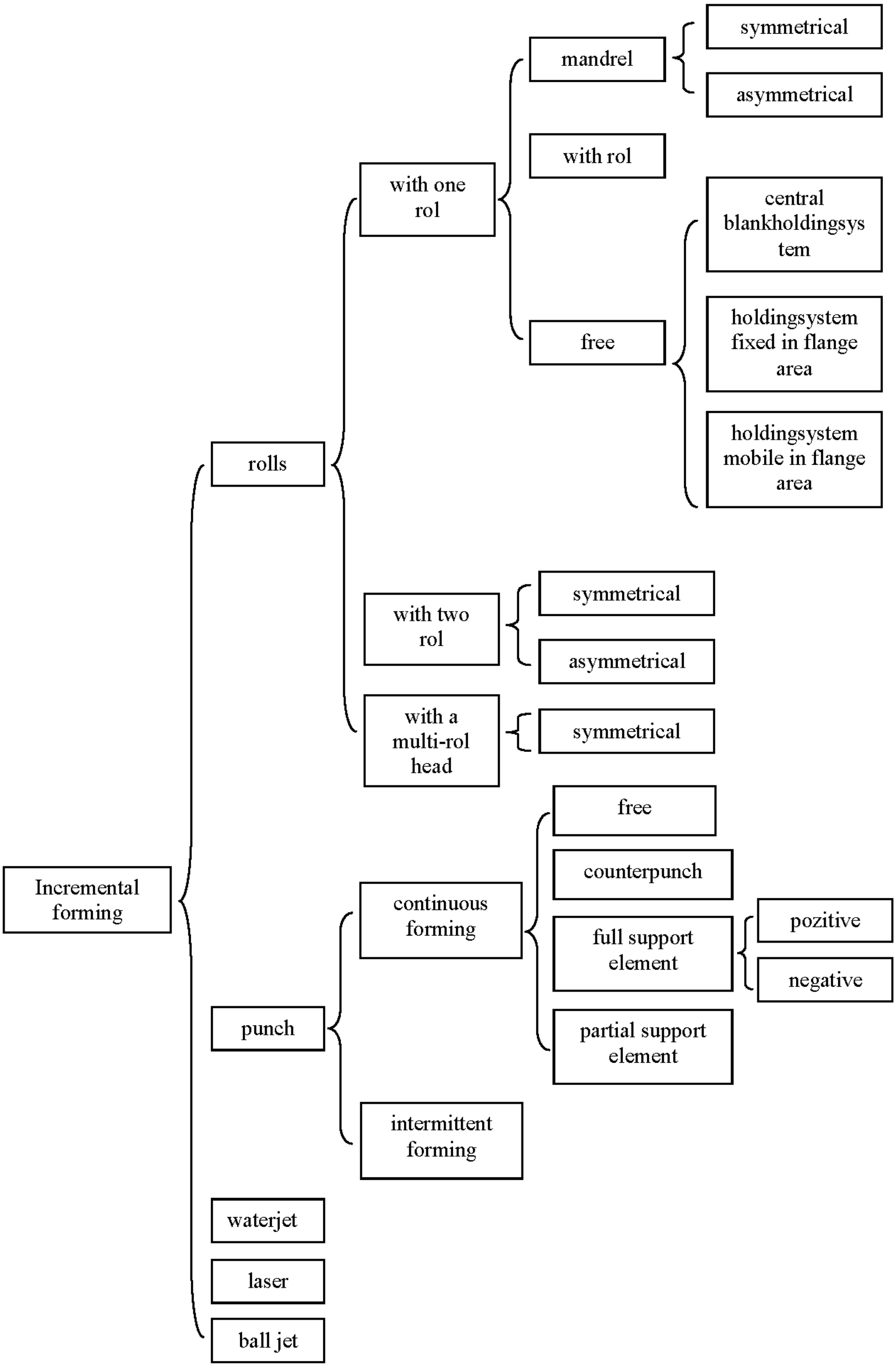


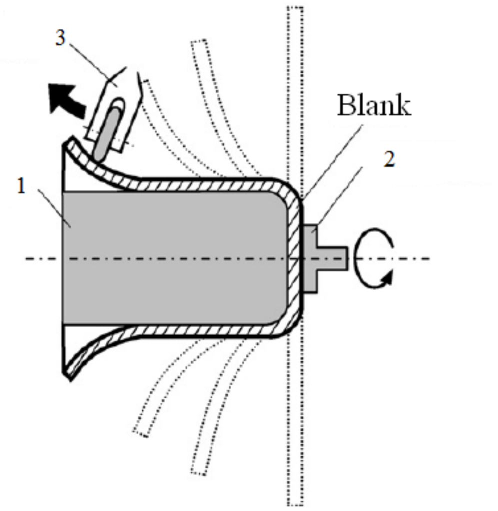
Fig. 2. 1 Classification of the incremental forming procedures

2.3 Main incremental forming processes

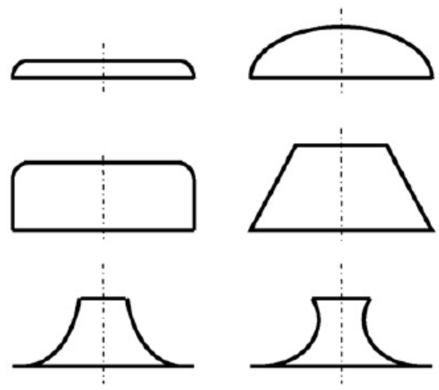
2.3.1 Roll forming

Roll forming is realised on special machines and the active element is constituted by one, two or several forming rolls. The blank's material is formed, generally, on a pin-type activ support element. The manner of applying the force is continuous, the contact between forming tool and material is permanent, while the forming focus point is moving as a result of the procedure's kinematics. This method allows the processing of most metallic materials used in metal forming operations. In some situations (thicker materials or materials that are harder to process), the forming can be done under hot conditions, by heating the blank's material.

The most employed procedure of this kind is the incremental forming with one roll and support pin. The disk-shaped blank made of sheet metal (fig. 2.2, a) is firmly fastened to the support pin 1 with the help of the pressing element 2 and the whole subassembly carries out a rotation motion. The forming roll 3 moves along a plane trajectory, materialising the part's generating line.



a)



b)

Fig. 2.2 Incremental forming with rolls without an intended thinning of the material

2.3.2 Incremental forming with a punch

In this incremental forming variant, the active tool is constituted of a small size punch. The contact between the forming tool and the blank is continuous, the procedure being generally carried out under cold conditions. A simplified scheme of the forming process is shown in figure 2.18.

The blank (fig. 2.18) is blocked on the contour in the blankholding system consisting of the support plate 1 and the blankholder ring 2. The punch 3 realises the incremental forming of the blank, tracing succesively trajectories with different perimeters. After completely going through a trajectory, the punch descends by one step.

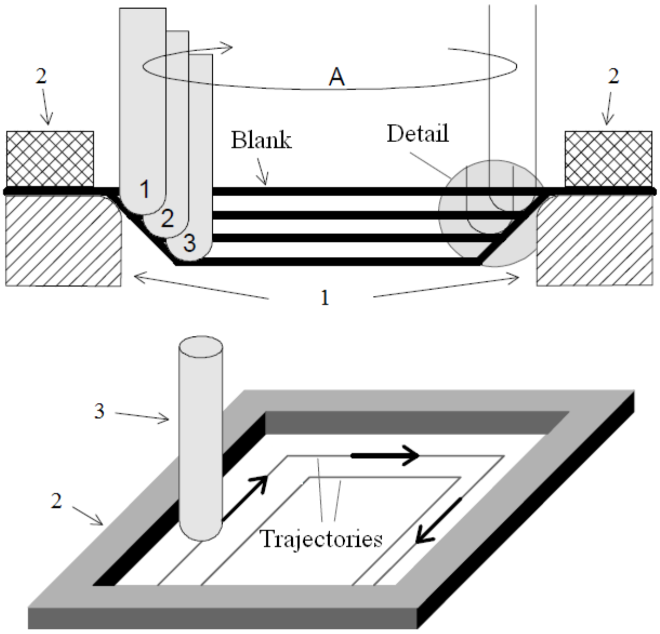


Fig. 2.18 Incremental forming with a punch

The process is found in the speciality literature as "single point" incremental forming, although in reality the contact between punch and blank is realised on a small-size area.

The process has several variants depending on the employed active support element and on the type of blankholding system, variants that are presented in figure 2.19. Variants a, b and c have a fixed blankholding system, while variants d and e have a mobile blankholding system, that is moving along the vertical axis as the tool forms the material. The first three configurations are called negative incremental forming, while the last two configurations are called positive incremental forming. Also, variants b, c, d and e use an active support element, for which reason they are called "two points" incremental forming.

The active support element can be a counterpunch (b) or an active plate (c). For the positive incremental forming, the active support element is placed inside the blank, the forming being carried out on the outside. The support can be total (d) or partial (e).

The incremental forming procedure with a small size punch has developed following the improvement of the CNC milling machines and the development of CAD/CAM software for generating the tool trajectories. The idea of an incremental forming with a small size punch was introduced for the first time in a patent by Leszac in 1967 [127].

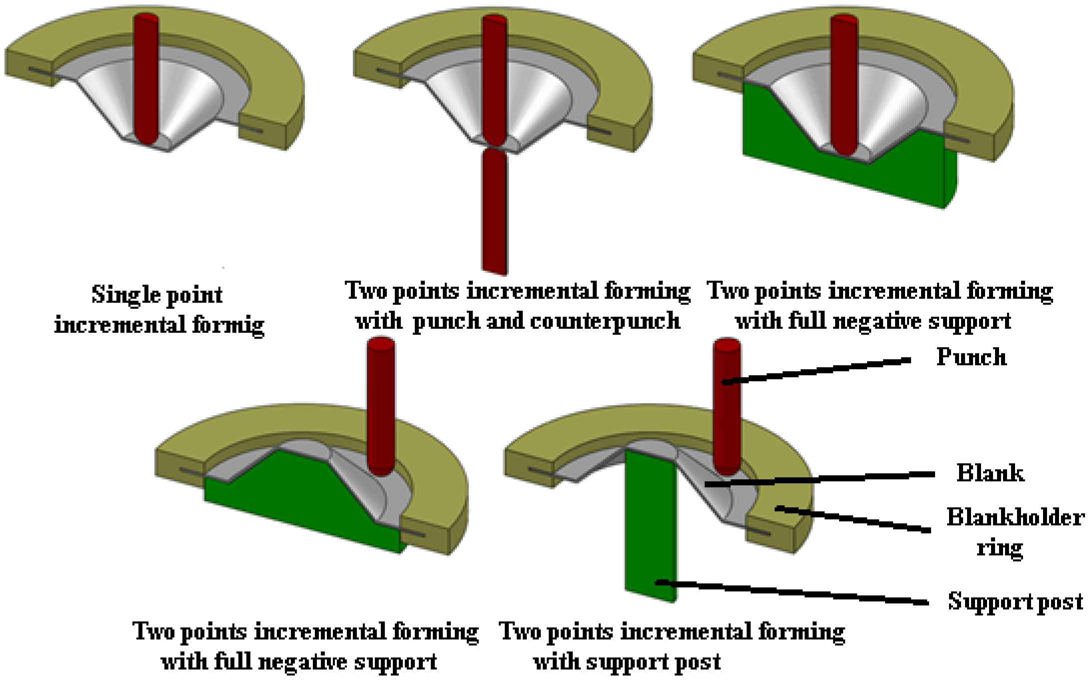


Fig. 2.19 Variants of the incremental forming procedure with a punch

Chronologically, first there was studied the "two points" incremental forming by Powell and Andrew [166], used afterwards by Matsubara [135] for realising assymetrical parts in small batches and at low costs.

Later, the "single point" incremental forming was studied by Jeswiet [89], Leach [126] and Fratini [55]. These have shown that forming can be done on a milling machine with three numerical controlled axes. Using CAD/CAM software, there can be generated the tool's trajectories and there can be thus manufactured complex parts. between the device presented in figure 2.20 and the one used by Jeswiet and Leach is a major difference: the lack of a support rod or of the active plate. This forming type creates in the blank stress and strain states that are different from those encountered in the "two points" incremental forming.

For both types of incremental forming with punch, the forming equipment consists mainly of:

- the active forming element (the punch);
- the blankholding system;
- the active support element (if necessary);
- the machine generating the movements needed for the forming.

2.3.3 Incremental forming with waterjet

The technology of processing with the help of a waterjet is used in many domains, such as the automotive industry, aeronautics, mining, medicine and even in food processing. Generally, it is used as a cutting procedure, but it can be also used as a procedure for surface cleaning, degreasing, strain hardening etc.

There were investigated also other possibilities for using the waterjet-based technology. One of these possibilities is to use the waterjet as active element in incremental forming.

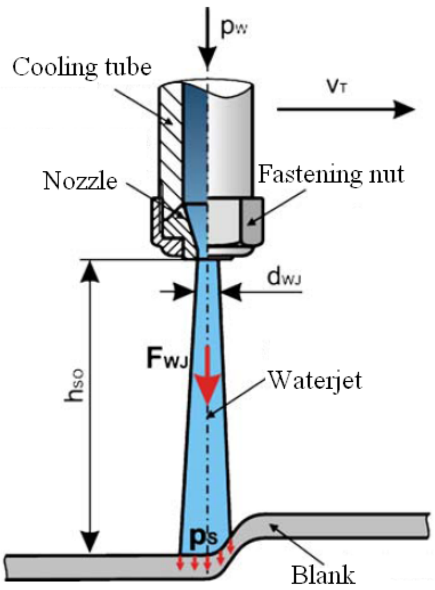


Fig. 2.37 Important parameters of the procedure

The first attempt in this regard was realised by Iseki [84]. Based on his results, there were carried out similar investigations at the University of Ljubljana, Slovenia, in cooperation with the University of Applied Sciences Argau of Sweden, where a waterjet cutting system was modified in order to realise the incremental forming of an aluminium sheet with a thickness of 0.5 mm [96, 97].

The work principle and the most important parameters of the incremental forming process are presented in figure 2.37.

2.3.4 Incremental forming with laser

Incremental forming with laser is a new forming process for metal sheets made of stainless steel, light aluminium, magnesium and titanium alloys, that have large heat dilation coefficients. During the forming process with laser, strains are induced in a controlled manner into the blank by moving the laser beam on the material. The process (fig. 2.41) is used for realising bending operations and has several

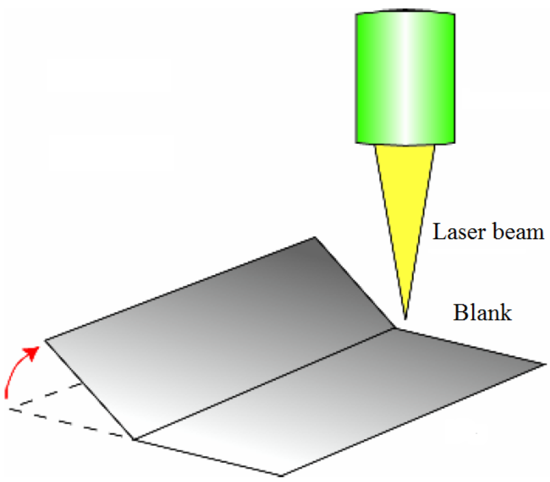


Fig. 2.41 Bending with a laser beam

advantages over other traditional procedures, because the material's forming does not require external forces, it being done only by means of the laser beam.

2.3.5 Incremental forming with a ball jet

The active forming element can also be a ball jet directed at a certain speed towards the blank. The forming with ball jet is employed industrially for realising components for airplanes. The known applications are especially slightly curved parts [119]. As a work principle, ball jet forming is, however, suitable also for parts with larger curvatures.

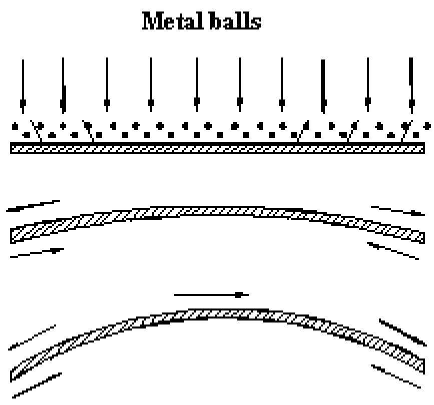


Fig. 2.43 Scheme of the forming procedure with a ball jet

In this case, the blank is free, it is not fastened in a special device on the contour. The blank is bombarded with balls so that, according to the balls' kinetic energy, in the material there is induced a tensile or a compression stress state (fig. 2.43) that can lead to forming a concave or convex surface. Due to the fact that the blank is not fastened, it can be formed in its entirety. For long parts, the "bombarding" equipment is moving along the blank [63].

The main application domains for this incremental forming procedure are:

- automotive industry;
- architecture: decorative pannels;
- personalised products;
- medicine: prostheses, dental crowns;
- aeronautical industry;
- shipbuilding industry.

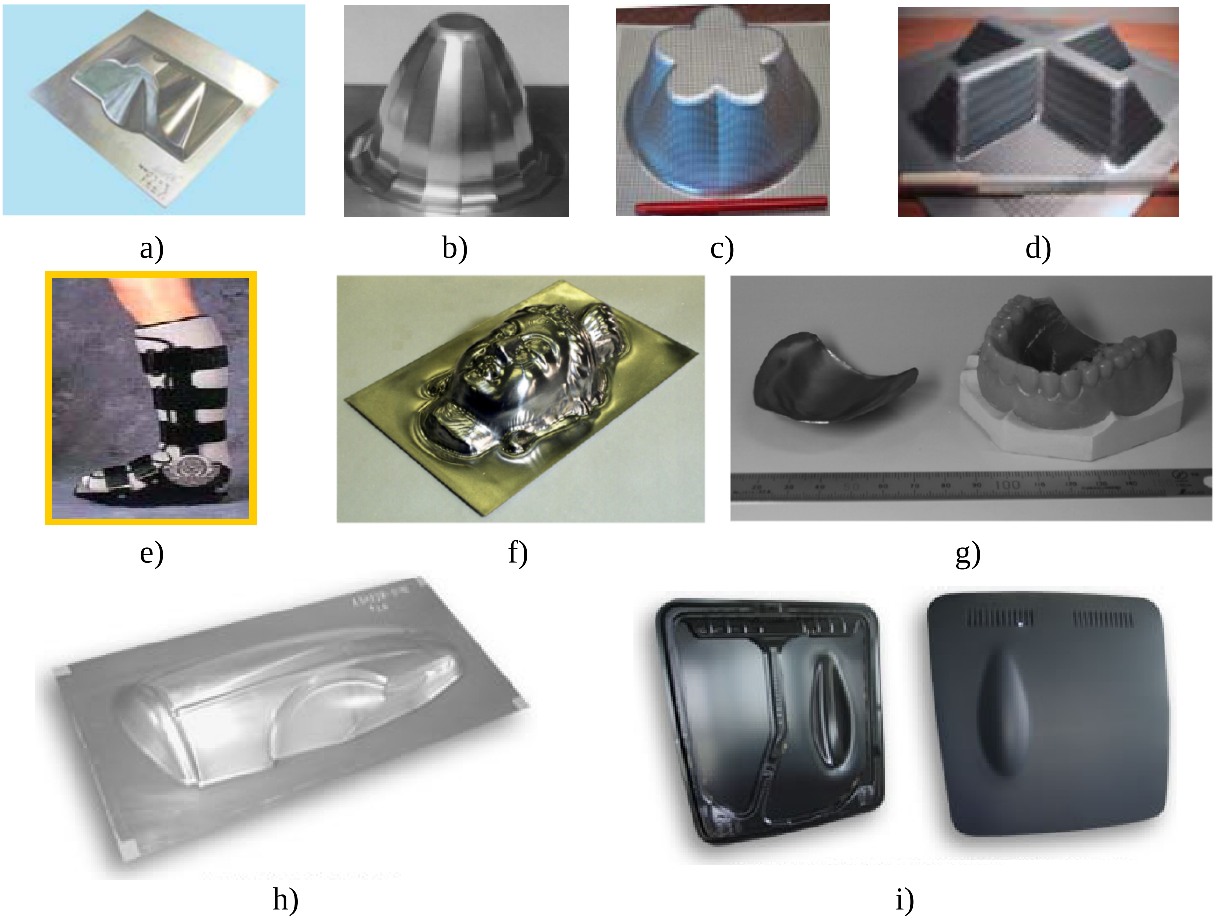


Fig. 2.44 Parts obtained through incremental forming

2.4 Researches regarding incremental forming

Within the incremental forming processes, there have been identified a very large number of papers dealing with this topic. There have been carried out analytical researches, researches through the finite elements method and experimental researches. In the following, there will be presented in short the main contributions in the domain, grouped according to the type of research (analytical, MEF, experimental) but also according to the employed tool.

2.4.1 Analytical researches

The analystical researches have focused generally on determining the forces in the process. In this area, there can be mentioned the works of Dröge [49], Avitzur şi Yang [18], Kalpakcioglu [102-103], Kobayashi [118], Sortais [180], Hayama şi Murota [66], Wang [188], Hayama [67-68], Kim and others [111].

In the case of the incremental forming with a punch, in the speciality literature there have been identified theoretical approaches concerning the determining of the forming degree in the material and the forming forces, in papers authored by Iseki [84, 85], Oleksik [155] and Pohlak [165].

Another way of tackling the process was identified in the analytical studies realised by Martins [132] and Silva [178] who consider the material's behaviour during forming to be similar to that of a membrane, in order to explain the phenomenon of fractures occuring in the part.

2.4.2 Researches through the finite element method

Analytical models are generally limited to determining strains and forces in the process. For a broader study there are employed numerical methods, especially the finite element method. Through this method it is possible to determine the influence of all parameters within the forming process.

Incremental forming is characterised by the fact that the forming area is small and shifts continuously its position, so that the finite element analysis requires the usage of a fine mesh and of a large number of time increments. For this reason, the running time of an analysis is rather long. Consequently, one of the research directions was focused on identifying simplifying hypotheses that would allow the reduction of the time required for such an analysis.

Active in the numerical simulation of the incremental forming procedure with a roll were Alberti [3], Liu [128], Mori and Nonaka [149], Quiglez and Monagah [168-169], Klocke and Wehrmeister [117], Lu [130], Kleiner [114] and Klimmek [116].

Yamashita [188] has realised the numerical simulation of the "single point" incremental forming with a punch in order to analyse the influence of the trajectory type on the forces and part precision.

Micari [141], Hirt [78], Bambach [21], Ambrogio [9], He [71, 72] and Henrard [74] had a sustained contribution to developing finite element models of the incremental forming procedure with punch.

2.4.3 Experimental researches

At the study of the incremental forming with a roll/with rolls, the experimental research methods were used to emphasise the mechanism of forming and the evolution of deformations, the mechanism of fracture and its emphasising, the forces required for the forming, the surface quality, the optimisation of the product's geometry etc.

For the studying of the forming mechanism and the evolution of strains in incremental forming with a roll/with rolls, there have been used two methods for emphasising the deformations: the method of full holes [18] and the method of meshes (square mesh [101-102] or circle type mesh [167]).

For the study of the incremental forming with a punch, the experimental research methods were used in order to emphasise: the mechanics of the forming process [87], the forces required for the forming [50, 53, 143], the precision of the obtained surface [12], the formability of various materials [81, 174, 94], the optimal punch trajectory [15, 16] etc.

2.5 Conclusions

The incremental forming process of metal sheets is a modern cold forming method. It appeared as a consequence of the more and more diversified requirements of the customers. Since it is a flexible forming procedure, the manufacturing of parts through this procedure requires tools with a simple structure, realised at low costs and often reusable for various types of parts. There exist, in a development stage, several incremental forming processes, presented also in this chapter, such as the forming with rolls, the forming with waterjet, the forming with laser or the forming with a small size punch.

The incremental forming with a small size punch is the most developed one, due to the fact that it allows the easy manufacturing of both industrial parts in small batches and of prototypes. It requires only a coordinates milling machine, for realising the spatial motion of the forming tool, a small size punch and a support for fastening the material.

Although incremental forming with a punch is a viable process, several challenges remained. One of these is the reduction of the material's springback which currently keeps the procedure's precision at a level of 1.5 mm. It is neecessary to develop methods for compensating the springback, that would allow designers to reach the high precisions required by the products.

Another necessity is to determine the methods for obtaining the Forming Limit Diagrams for various combinations of materials and thicknesses.

Another research direction is to determine the strain state and the relative thinning of the material function of the material type, its thickness, the punch diameter, the part geometry.

The classical pressing processes will continue to be used, for economic reasons. A challenge is, however, the adaptation of the incremental forming process for mass production. At high processing speeds and with an improved product quality, it could be an alternative to the classical forming processes, especially due to its flexibility.

The research directions tackled within the doctoral thesis, resulted from the analysis and synthesis of the state of the are are focused on:

- determining the distribution of strains in incrementally formed parts;
- the study of the influence of geometrical parameters (punch diameter, size of the vertical pitch, sloping angle of the part's wall etc.) on the maximal values of the main strains and of the relative thinning;
- the study of the influence of the forming manner on the distribution of strains in the part and their maximal values;
- determining the forming forces resulting during the process and their influence factors.

3 THEORETICAL RESEARCHES REGARDING THE INCREMENTAL FORMING OF THIN METAL SHEETS

3.1 Introduction

In the analysed speciality literature, the theoretical researches regarding incremental forming were focused on determining the forming forces, taking into account a plane state of deformation in the material, its anisotropy and various process-related parameters [84, 85, 155, 165]. Starting from these elements, the theoretical researches comprised in the current thesis had following objectives:

- determining mathematical relationships by means of which there can be determined the strain value on two directions, a vertical one and one in the sheet's plane, at the moment when the punch realises an indexing of the pitch on vertical direction;
- determining mathematical relationships by means of which there can be determined the values of forces on two directions, a vertical one and one in the sheet's plane, at the moment when the punch realises an indexing of the pitch on vertical direction;
- the study of the variation of strains and forces function of the parameters that occur in the calculations.

3.2 Determining the calculus relationships for strains and forces at the incremental forming with a punch

3.2.1 Determining the calculus relationships for the strains

For the calculus of strains occuring in the incremental forming procedure, there will be taken into account a die (active plate) with square contour.

Figure 3.1 presents the geometrical model of the work scheme proposed for the forming with an active plate with square contour.

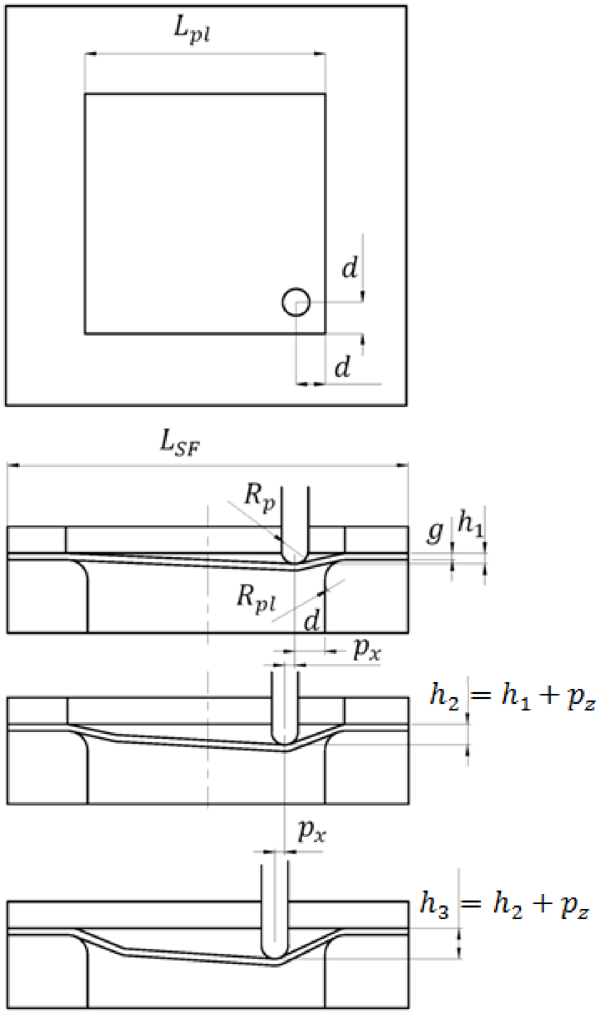


Fig. 3.1 Geometrical model for the active plate with square contour

This method was elaborated starting from the calculus method fundamented by Professor Hideo Iseki [84-85], who used a simplifying hypothesis, namely that the blank is stressed in a plane strains state, a method further developed by Oleksik [155], who takes into account also the presence of the angle δ. By introducing this angle, the method's precision increases, but it also complicates the mathematical algorithms used for solving it.

Within this mathematical model, there will be introduced two parameters: the pitch on vertical direction p_z and the pitch on horizontal direction p_x. This mathematical model aims to determine the strains and forming forces at the beginning of each penetration of the punch on vertical direction in the material. The geometrical parameters intervening in the calculus are: the spherical punch radius R_p, the filleting radius of the die R_{pl}, the side length of the opening of the lower part of the blankholding system L_{pl}, the distance between the border of the die and the punch *d*, the material thickness *g*, the penetration depth of the punch in the material *h*, the blank diameter D_{sf} and the pitch on the two directions, p_x and p_z. Function of these parameters, there will be determined: the dimensions of the contact angles θ_i and δ_i, the segments l_{1i}, l_{2i}, l_{3i}, l_{4i}, l_{5i}, l_{6i}, l_{7i}, l_{8i} (fig. 3.2-3.4). Using these geometrical parameters and considering that the maximal strain on the direction x is located at the level of the contact arcs l_{3i} and l_{4i} and that the other segments suffer only minor strains that can be neglected, there will be determined the logarithmic forming degrees on the direction *x*. Based on the first law of plastic deformation (the law of constant volume), in a later phase there will be determined the strain on the direction of the blank material's thickness.

As a start, there are introduced following notations in order to simplify the formulas that follow:

$$\rho_p = R_p + \frac{g}{2}; \tag{3.1}$$

$$\rho_{pl} = R_{pl} + \frac{g}{2}; \tag{3.2}$$

$$L = L_{pl} + 2 \cdot R_{pl}. \tag{3.3}$$

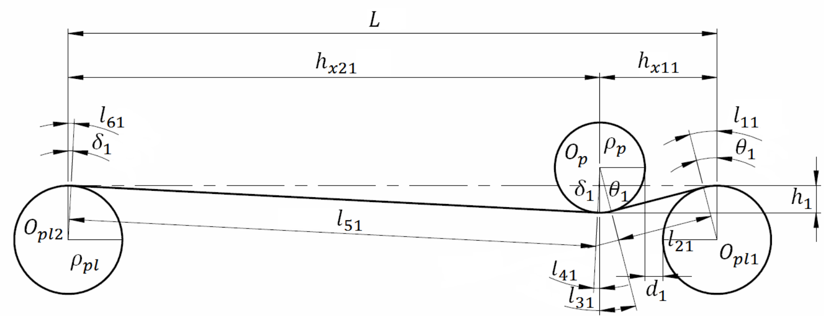


Fig. 3.2 Elements that define the geometry of the work scheme for the first step

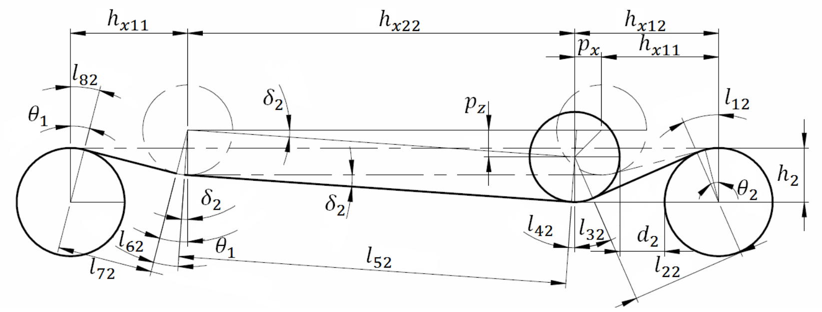


Fig. 3.3 Elements that define the geometry of the work scheme for the third step

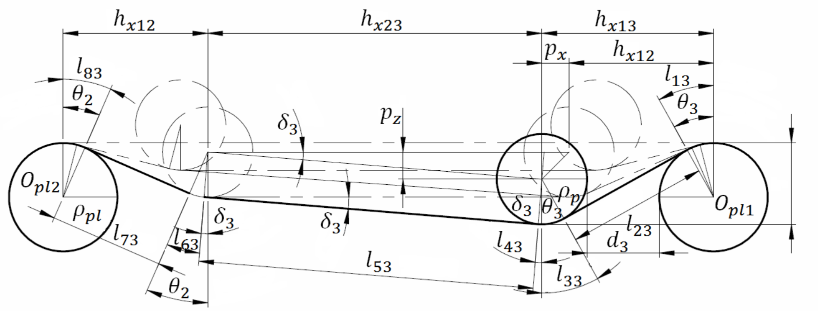
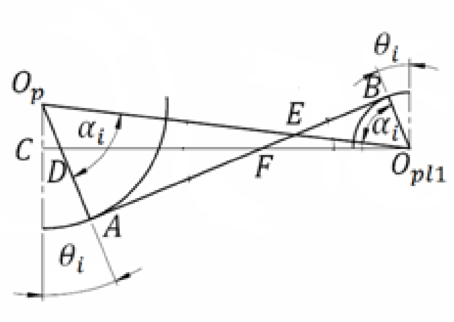


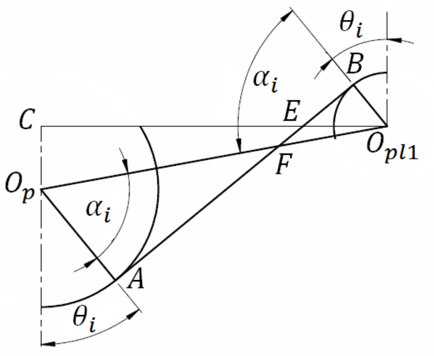
Fig. 3.4 Elements that define the geometry of the work scheme for the third step

3.2.1.1 Determining the contact angle θ_i

There can be distinguished two cases: the case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die (fig. 3.5, a) and the case in which the centre of the circle is located below the centre of the mentioned circle arc (fig. 3.5, b).



a) The case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die



b) The case in which the centre of the circle that defines the punch is located below the centre of the circle arc that defines the filleting radius of the die

Fig. 3.5 Determining the angle $\boldsymbol{\theta_i}$

After calculations, following relationships for the angle Θ_i result:

$$\theta_i = \arctan\left(\frac{\rho + d_i}{\rho - h_i}\right) - \arccos\left(\frac{\rho}{\sqrt{(\rho + d_i)^2 + (\rho - h_i)^2}}\right), \tag{3.15}$$

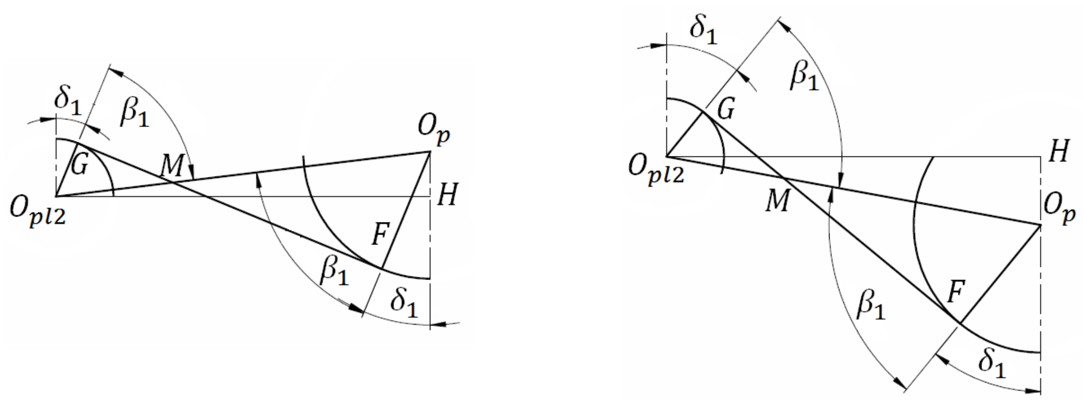
for the case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die and

$$\theta_i = -\arctan\left(\frac{\rho + d_i}{h_i - \rho}\right) + \arccos\left(\frac{\rho}{\sqrt{(\rho + d_i)^2 + (h_i - \rho)^2}}\right), \tag{3.20}$$

for the case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die.

3.2.1.2 Determining the contact angle **δ**$_i$

Calculus of the angle for the first step



a) The case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die

b) The case in which the centre of the circle that defines the punch is located below the centre of the circle arc that defines the filleting radius of the die

Fig. 3.6 Determining the angle δ_1

After the calculations, following relationships for the angle δ_1 result:

$$\delta_1 = \arctan\left(\frac{L-\rho-d_1}{\rho-h_1}\right) - \arccos\left(\frac{\rho}{\sqrt{(L-\rho-d_1)^2+(\rho-h_1)^2}}\right), \qquad (3.32)$$

for the case in which the centre of the circle that defines the punch is located above the centre of the circle arc that defines the filleting radius of the die and

$$\delta_1 = -\arctan\left(\frac{L-\rho-d_1}{h_1-\rho}\right) + \arccos\left(\frac{\rho}{\sqrt{(L-\rho-d_1)^2+(h_1-\rho)^2}}\right), \qquad (3.35)$$

for the case in which the centre of the circle that defines the punch is located below the centre of the circle arc that defines the filleting radius of the die.

Calculus of the angle for the second step

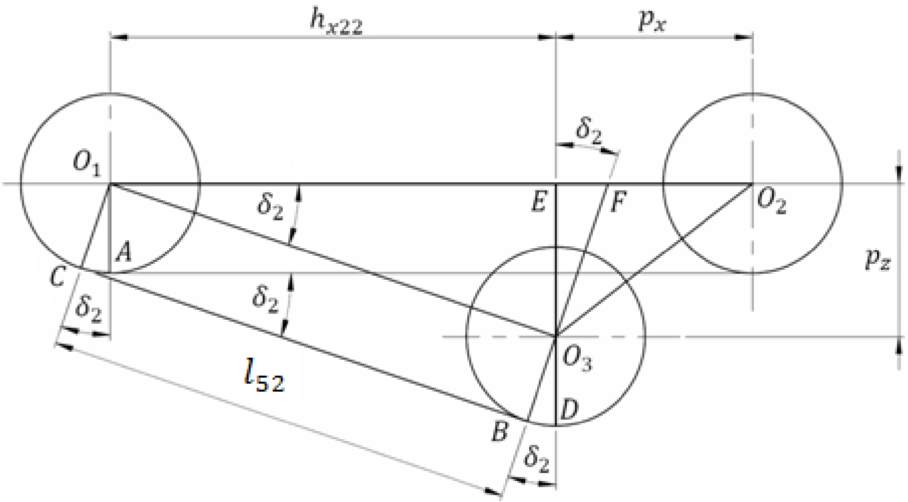


Fig. 3.7 Determining of the angle δ_2

After calculations, following relationship for the angle δ_2 results:

$$\delta_2 = \arctan\left(\frac{p_z}{L - p_x - 2*(\rho + d_1)}\right). \tag{3.39}$$

Calculus of the angle for the third step

Using the same reasoning as for the second step, there results the relationship:

$$\delta_3 = \arctan\left(\frac{p_z}{L - p_x - 2*(\rho + d_2)}\right). \tag{3.40}$$

3.2.1.3 Calculus of the length of segments l_i

Knowing the values of the two contact angles, there have been calculated the lengths of the segments l_i for each step.

Calculus of the length of the segments l_i for the first step

$$L_1 = L = L_{pl} + 2 \cdot R_{pl}; \tag{3.41}$$

$$l_{11} = \frac{\pi \cdot \rho_{pl} \cdot \theta_1}{180^\circ}; \tag{3.42}$$

$$l_{21} = (\rho + d_1) \cdot \cos\theta_1 - (\rho - h_1) \cdot \sin\theta_1. \tag{3.51}$$

$$l_{31} = \frac{\pi \cdot \rho_p \cdot \theta_1}{180^\circ}; \tag{3.52}$$

$$l_{41} = \frac{\pi \cdot \rho_p \cdot \delta_1}{180^\circ}. \tag{3.53}$$

$$l_{61} = \frac{\pi \cdot \rho_{pl} \cdot \delta_1}{180^\circ}; \tag{3.55}$$

$$l_{71} = 0; \tag{3.56}$$

$$l_{81} = 0. \tag{3.57}$$

Calculus of the length of the segments l_i for the second step

$$L_2 = 2(l_{11} + l_{21} + l_{31}) + (L_1 - 2h_{x11}). \tag{3.58}$$

$$l_{12} = \frac{\pi \cdot \rho_{pl} \cdot \theta_2}{180^\circ}; \tag{3.59}$$

$$l_{22} = (\rho + d_2) \cdot \cos\theta_2 - (\rho - h_2) \cdot \sin\theta_2; \tag{3.60}$$

$$l_{32} = \frac{\pi \cdot \rho_p \cdot \theta_2}{180^\circ}; \tag{3.61}$$

$$l_{42} = \frac{\pi \cdot \rho_p \cdot \delta_2}{180^\circ}. \tag{3.62}$$

$$l_{52} = \sqrt{h_{x22}^2 + p_z^2}. \tag{3.64}$$

$$l_{62} = \frac{\pi \cdot \rho_{pl} \cdot (\theta_1 - \delta_2)}{180^\circ}. \tag{3.65}$$

$$l_{72} = l_{21}; \tag{3.66}$$

$$l_{82} = l_{11}. \tag{3.67}$$

Calculus of the length of the segments l_i for the third step and for the following steps

Using the same reasoning as for the second step, there can be obtained relationships for both the initial blank length and for the lengths of segments l_i.

As can be noticed in the above equations, starting with the second step the lengths of segments l_i and the initial blank length are determined based on the same equations, the only difference being the index that represents the number of the step for which the lengths were determined.

3.2.1.4 Determining the calculus relationship for the logarithmic forming degree on the x direction

In order to determine the logarithmic forming degree on the x direction, there will be determined the size of the segment that suffers the largest strain based on the above calculations. Considering that the segments that suffer the maximal strain are those in direct contact with the punch (l_{3i} and l_{4i}), the logarithmic forming degree is determined as logarithm of the ratio between the size of these segments after forming and the size before the forming. Thus:

$$\varepsilon_{xi} = \ln\left(\frac{l_{3i} + l_{4i}}{L_i - l_{1i} - l_{2i} - l_{5i} - l_{6i} - l_{7i} - l_{8i}}\right). \tag{3.77}$$

After making the necessary replacements, i.e. replacing the segment lengths with the formulas presented earlier, there results the size of the logarithmic forming degree on the direction x.

First step

$$\varepsilon_{x1} = \ln\left(\frac{\dfrac{\pi \cdot \rho_p}{180} \cdot (\theta_1 + \delta_1)}{L_1 - \begin{pmatrix} \dfrac{\pi \cdot \rho_{pl}}{180} \cdot (\theta_1 + \delta_1) + L_1 \cdot \cos\delta_1 + (\rho + d_1) \cdot (\cos\theta_1 - \cos\delta_1) \\ -(\rho - h_1) \cdot (\sin\theta_1 + \sin\delta_1) \end{pmatrix}}\right). \qquad (3.78)$$

Second step

$$\varepsilon_{x2} = \ln\left(\frac{\dfrac{\pi \cdot \rho_p}{180} \cdot (\theta_2 + \delta_2)}{L_2 - \begin{pmatrix} \dfrac{\pi \cdot \rho_{pl}}{180} \cdot (\theta_2 + 2 \cdot \theta_1 - \delta_2) + \sqrt{h_{x22}^2 + p_z^2} + (\rho + d_2) \cdot \cos\theta_2 \\ -(\rho - h_1) \cdot \sin\theta_2 + (\rho + d_1) \cdot \cos\theta_1 - (\rho - h_1) \cdot \sin\theta_1 \end{pmatrix}}\right). \qquad (3.79)$$

For all other steps, the segment lengths will be determined in the same manner as for the second step, so that the strains too will be determined with relationship (3.79) too.

3.2.2 Determining the calculus relationships for the forming forces

The forces in the incremental forming procedure were determined starting from the relationships developed by Oleksik in his doctoral thesis [155], but the employed relationships allow to determine the force for each forming step and take into account the modification of the geometrical parameters (δ_i, θ_i) when indexing the step. The equations based on which the forces were calculated are as follows:

$$F_{xi} = \frac{2}{\sqrt{3}} B_i \cdot g_0 \cdot e^{(-\varepsilon_{xi})} \cdot K \cdot (\varepsilon_0 + \varepsilon_{xi})^n \cdot \left(\frac{1}{e^{\mu \cdot (\theta_i + \delta_i)}} \cdot \cos\delta_i - \cos\theta_i\right); \qquad (3.83)$$

$$F_{zi} = \frac{2}{\sqrt{3}} B_i \cdot g_0 \cdot e^{(-\varepsilon_{xi})} \cdot k \cdot (\varepsilon_0 + \varepsilon_{xi})^n \cdot \left(\frac{1}{e^{\mu \cdot (\theta_i + \delta_i)}} \cdot \sin\delta_i + \sin\theta_i\right); \qquad (3.84)$$

where:

B_i is the contact perimeter between material and punch;

g_0 – the initial thickness of the blank;

K – strength coefficient;

n – strain hardening coefficient;

ε_0 – remaining strain;

ε_x – strain on the x direction;

δ_i, θ_i – contact angles;

μ – friction coefficient.

3.3 Theoretical study of the variation of strains and forces

According to the calculus relationships (3.78), (3.79), (3.83), (3.84), the forming strains and forces depend on several parameters. It is considered that the main parameters are the ones presented in table 3.1, table that emphasises also the variation domain taken into account as part of the theoretical researches.

Table 3.1

Parameter	**Values**		
Diameter of the spherical punch D_p [mm]	7	8	9
Side lengt of the opening of the lower part of the blankholding system L_{pl} [mm]	55	60	65
Material thickness g [mm]	0,5	0,7	1
Pitch on vertical direction p_z [mm]	1	1,25	1,5
Sloping angle of the part's wall θ [°]	33,7	45	63,43

The relationships were solved by means of graphical-analytical methods with the help of the Mathcad 14 software package.

From these graphs, there can be noticed:

- a decrease of the logarithmic forming degree when the punch diameter increases and when the length of the die increases;
- an increase of the logarithmic forming degree when the vertical pitch increases, when the material thickness increases and when the sloping angle of the part's wall increases.

As an example, figure 3.8 shows the variation of the logarithmic forming degree function of the adopted vertical pitch.

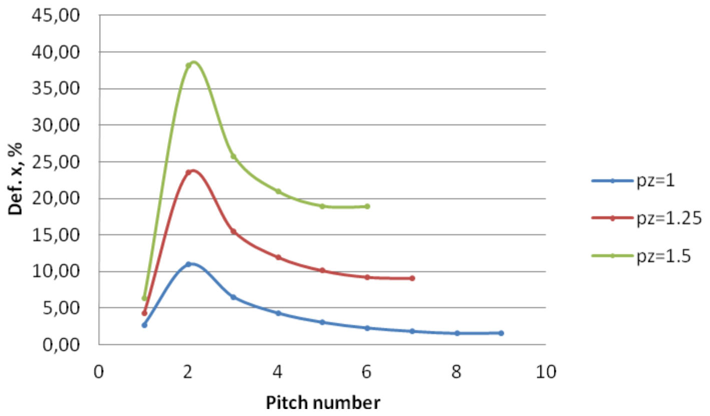
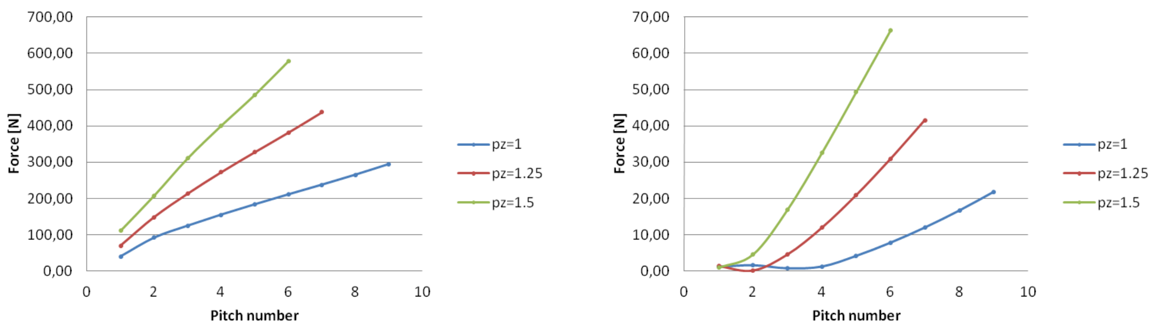


Fig. 3.8 Variation of the logarithmic forming degree function of the vertical pitch

The graphs show that:

- the forming forces F_x
    - decrease with the increase of the punch diameter and with the increase of the length of the die;
    - increase when the vertical pitch increases, when the material thickness increases and when the sloping angle of the part's wall increases;
- the forming forces F_z
    - decrease with the increase of the length of the die;
    - increase with the increase of the vertical pitch, of the punch diameter, of the material thickness and of the sloping angle of the part's wall.

As an example, figure 3.13 shows the variation of the forming forces function of the adopted vertical pitch.



a) Fz b) Fx

Fig. 3.13 Variation of the forming forces function of the adopted vertical pitch

3.4 Conclusions

The resulting conclusions are valid for a plane stress state in the material and only in the penetration area on a vertical direction of the punch, the area where, in the real case, there are encountered the maximal values for the strains and forces. Thus, there can be assessed, based on the theoretical study, the variation trends of the logarithmic forming degree and of the forces on the two directions function of the significant geometrical parameters, but the quantitative dimensions of these parameters cannot be determined with certainty.

A significant influence on the strains is that of the vertical pitch p_z, the angle of the part's wall θ and the punch radius R_p.

In the case of forces, the parameters of significant influence are the vertical pitch p_z, the blank material thickness g and the side length of the opening of the lower part of the blankholding system L_{pl}.

In reality, in the case of the incremental forming of the metal sheets, the strain state is spatial, complex and the material's real behaviour for such a loading is difficult to determine analytically. In order to better and more completely assess the material's behaviour, there are needed numerical simulations of the incremental forming process using the finite element method, a method that provides results that are much closer to reality.

4 NUMERICAL SIMULATION OF THE "SINGLE POINT" INCREMENTAL FORMING PROCSS USING THE FINITE ELEMENT METHOD

4. 1 Analysis method used for modelling

An overview of the analysis method used in the current thesis is given in the chart in figure 4.4. The chart presents in detail the phase of preprocessing the data corresponding to the physical model of the forming process. At the beginning, there are defined the formable and stiff bodies based on the blank's and the tools' geometry. The geometry is the one specific for the moment of process initiation. Based on the geometry of the formable body, this is meshed into finite elements. To the set of elements thus defined, there are also associated:

- material data, specifically the flow curve;
- geometrical data, namely the fact that the elements are of solid type and satisfy the incompressibility condition;

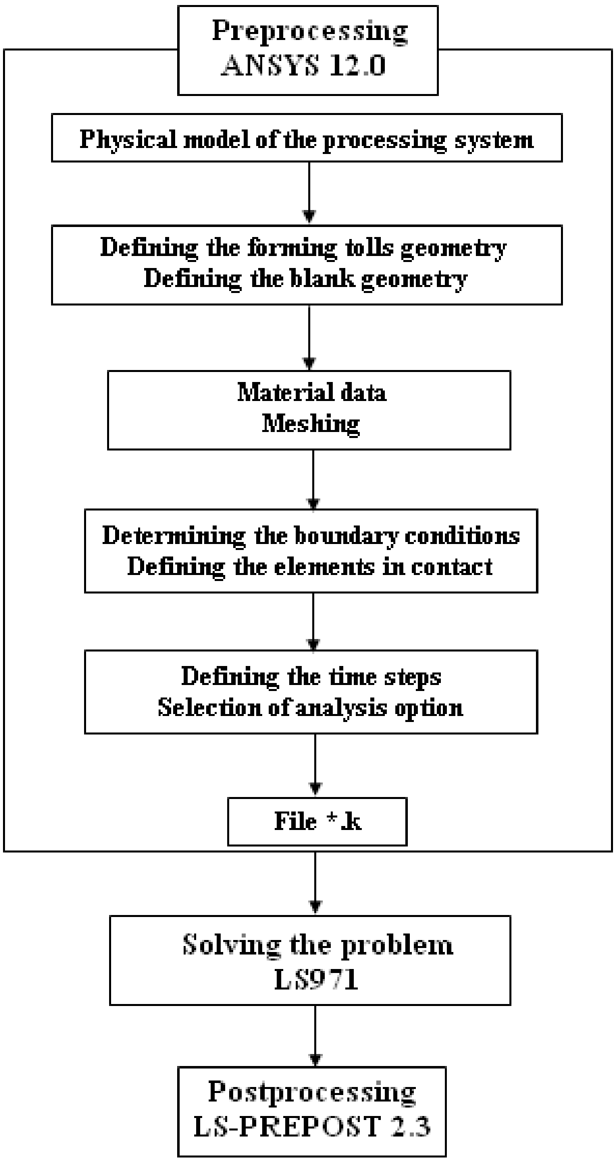


Fig. 4.4 MEF simulation algorithm

- the type of element; based on recommendations from the speciality literature.

4.2 Finite element models used in the study of the incremental forming process

The objectives of the researches through the finite element method were aimed at:

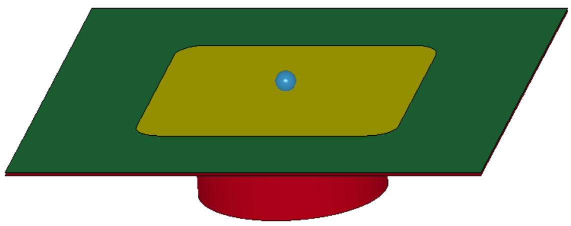
1. determining the influence of the geometrical parameters on the main strains and on the relative thinning;
2. determining the distribution of strains on the part and their evolution during the forming;
3. determining the forces and the energy consumed during the process;
4. determining the springback.

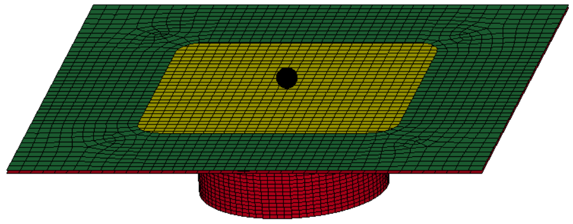
Table 4.1 presents the types of analyses carried out, the parameters taken into account and their variation domains. The number of the analysis type in the table corresponds with the number of the targeted objective.

Table 4.1

Parameter	**Variation domain**	**Analysis type**			
		1	2	3	4
Punch diameter D_p [mm]	6	x	-	-	-
	10	x	x	x	x
Vertical pitch p_z [mm]	1	x	x	x	x
	0,25	x	-	-	-
Material thickness g [mm]	0,8	x	x	x	x
	1,14	x	-	-	-
Number of integration points	7	x	x	x	-
	11	-	-	-	x
Trajectory type	rectilinear groove	x	x	x	x
	cone frustum	-	x	x	x
	pyramid frustum	-	x	x	x

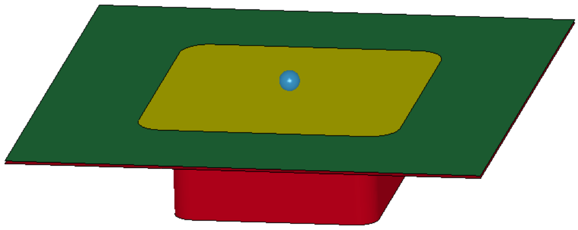
For studying the distribution of strains and the variation of forces during the incremental forming process, two parametric models were used as base for the finite element analyses.

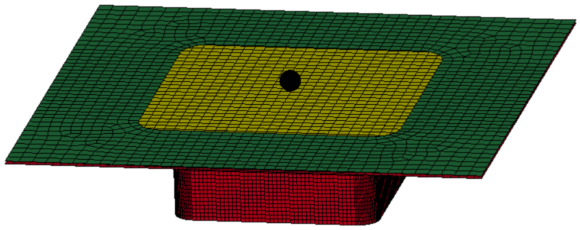




a) Geometrical model

b) Finite element model





c) Geometrical model

d) Finite element model

Fig. 4.5 Models used in the numerical analyses

All models were realised using as material aluminium. Table 4.2 presents the material data used in the numerical simulations.

Table 4.2

Thickness [mm]	*E [GPa]*	ν *[-]*	σ_c *[MPa]*	*K [MPa]*	*n [-]*	ε_0 *[mm/mm]*	r_0 *[-]*	r_{45} *[-]*	r_{90} *[-]*
0,8	61	0,34	122,69	447	0,209	0,002	0,711	0,457	0,473
1,14	66	0,34	136,06	455	0,194	0,002	0,770	0,499	0,729

4.3 Determining the influence of geometrical parameters on the main strains for the single point incremental forming procedure

The reason for this analysis is to emphasise the distribution of the main strains and of the relative thinning, during the single point incremental forming procedure for parts of straight groove type.

In the following, there is presented the specific strains state and the relative thinning on the direction of the punch's movement. This is represented in the figure succession 4.13 - 4.18.

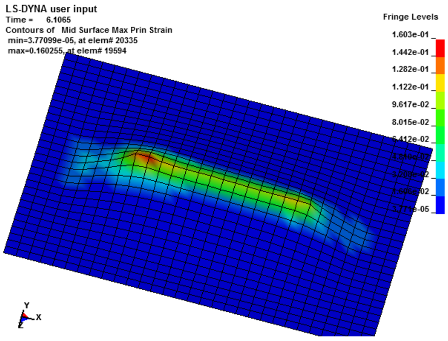


Fig. 4.13 Distribution of the major strain, ε_1 [mm/mm] for the forming of a straight groove

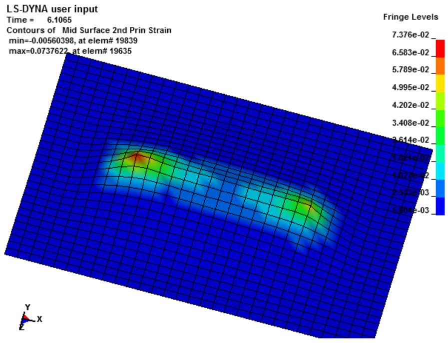


Fig. 4.14 Distribution of the minor strain, ε_2 [mm/mm] for the forming of a straight groove

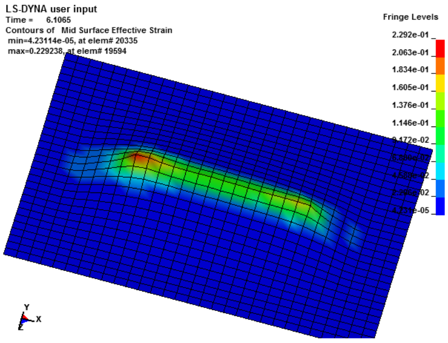


Fig. 4.15 Distribution of the equivalent strain, ε_{vM} [mm/mm] for the forming of a straight groove

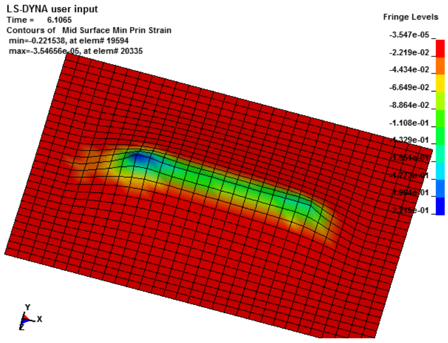


Fig. 4.16 Distribution of the strain on the thickness, ε_3 [mm/mm] for the forming of a straight groove

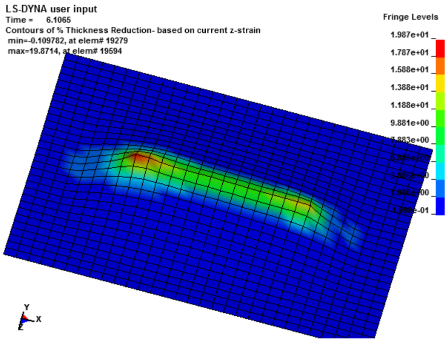


Fig. 4.17 Distribution of the relative thinning, s, % for the forming of a straight groove

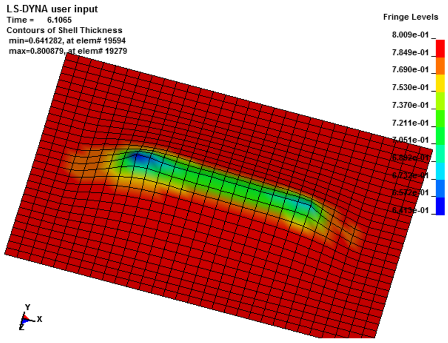


Fig. 4.18 Distribution of the material thickness, g [mm] for the forming of a straight groove

The mjor strain has maximal values along the punch's movement along the x direction, with a maximum in the initial penetration area on the z direction. Figure 4.13 presents the major strain and the variation pattern. The minor strain has maximal values in the punch penetration areas, with a maximum in the initial penetration area, as can be seen in figure 4.14. Figure 4.15 presents the equivalent von Mises strain, that reaches maximal values in the punch penetration areas and has a distribution on the part similar to that of the major strain.

The same phenomenon as in the case of the strains can be noticed in figures 4.17 and 4.18 for the case of the relative thinning of the material and of the variation of the sheet's thickness, respectively.

The cases taken into account and the maximal values of the results of the numerical analysis for all parameters considered are presented in table 4.3.

Table 4.3

Case	d_p [mm]	p_z [mm]	g [mm]	ε_1	ε_2	ε_3
C1	10	0,25	0,8	0,1865	0,1029	0,2802
C2	10	1	0,8	0,1955	0,0884	0,2767
C3	10	0,25	1,14	0,1986	0,1152	0,3161
C4	10	1	1,14	0,2179	0,1097	0,3046
C5	6	0,25	0,8	0,198	0,1211	0,3142
C6	6	1	0,8	0,2155	0,09209	0,3024
C7	6	0,25	1,14	0,2127	0,1354	0,34
C8	6	1	1,14	0,2359	0,1027	0,3336

As can be noticed from the table, the smaller the vertical pitch, the larger the minor strains and the relative thinning are. An increase in the punch diameter leads to an increase of the values of all studied characteristics, major strains and relative thinning.

4.4 Distribution of the strains on the part for the single point incremental forming

In order to determine the distribution of strains at incremental forming, a finite element model was chosen that used a blank with a mesh similar to the one employed for determining the influence of geometrical parameters.

For this study, there have been taken into account three types of trajectories: a trajectory for describing a straight groove with indexing on z at each end, a trajectory for describing a cone frustum and a trajectory for describing a pyramid frustum. Within the simulations, there has been considered a punch with a diameter of 10 mm and the punch's vertical pitch of 1 mm and as material aluminium with a sheet thickness of 0.8 mm. In the following, in this abstract there are presented the main results obtained for realising a pyramid frustum.

Pyramid frustum

From the analysis of figures 4.35 - 4.40 it can be noticed that the major strain and the equivalent strain have an uneven distribution on the formed blank's surface, being noticeable a pronounced localisation of the maximal strains along the trajectory followed by the punch. This can be explained by the gradual reduction of the cross-section located in front of the forming focus point, as it moves on.

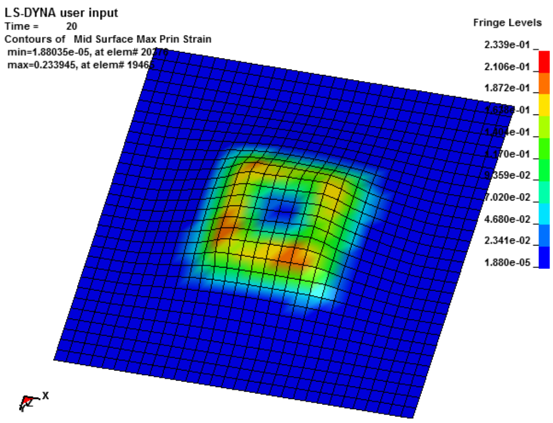


Fig. 4.35 Distribution of the majorstrain, ε_1 [mm/mm] for the forming of a pyramid frustum

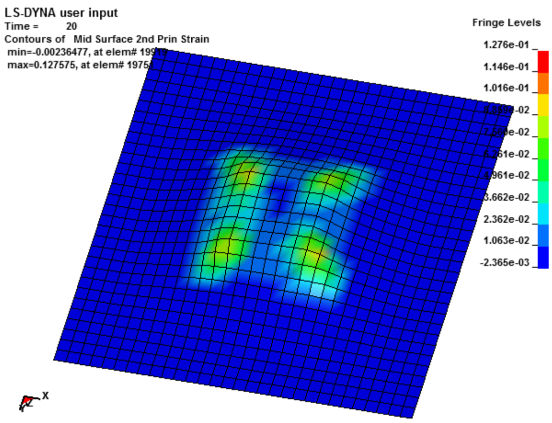


Fig. 4.36 Distribution of the minor strain, ε_2 [mm/mm] for the forming of a pyramid frustum

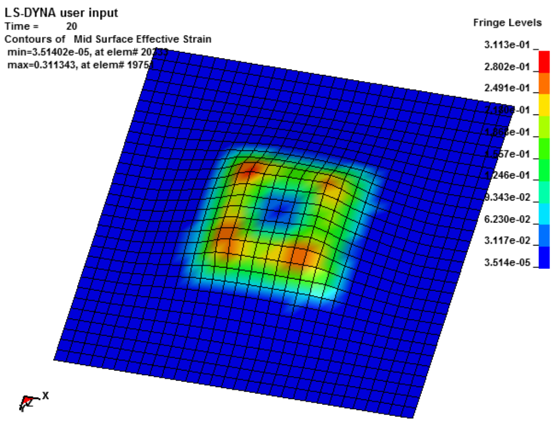


Fig. 4.37 Distribution of the equivalent strain, ε_{vM} [mm/mm] for the forming of a pyramid frustum

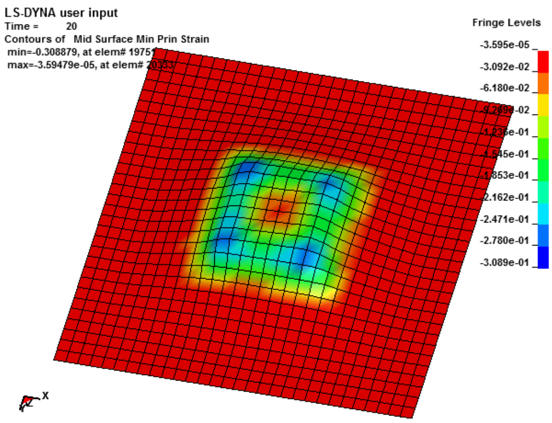


Fig. 4.38 Map of the strain distribution on the thickness, ε_3 [mm/mm] for the forming of a pyramid frustum

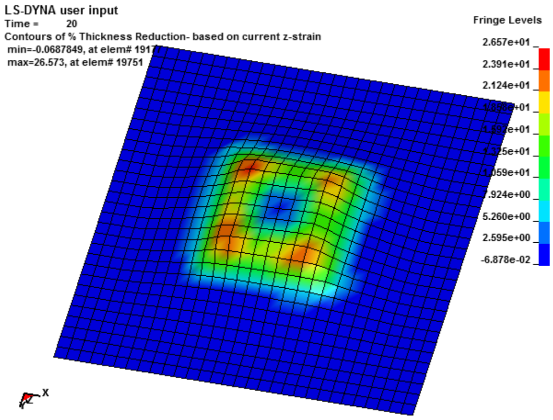


Fig. 4.39 Distribution of the relative thinning of the material, s, % for the forming of a pyramid frustum

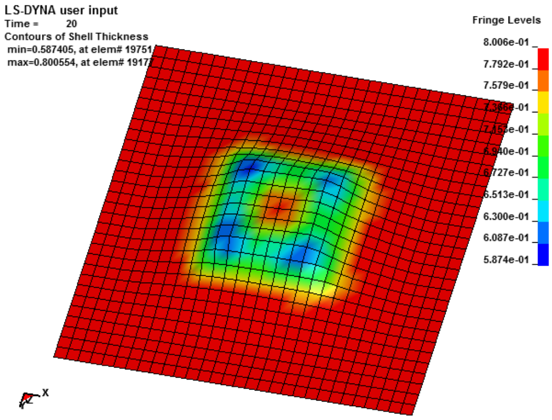


Fig. 4.40 Distribution of the material's thickness, g [mm] for the forming of a pyramid frustum

The minor strain has maximal values in the part's corners, with a maximum in the corner where the punch realises the feed on vertical direction.

The remark regarding the major strain is reconfirmed also at the level of the sheet's thickness and of the relative thinning registered at the end of the simulation (fig. 4.39 şi 4.40).

In order to highlight the evolution of the major strains, of the relative thinning and of the displacement on the z axis on the resulted part there have been chosen five nodes, as follows: a node (56644) located exactly at the border of the punch's penetration area at the first step, another one located in the punch's penetration area at the first step (54475), another one in the middle area between the first and the last step (52799), another one in the penetration area from the last step (52063) and the last one in the part's central area (48446). The position of the elements selected for the analysis is presented in figure 4.41.

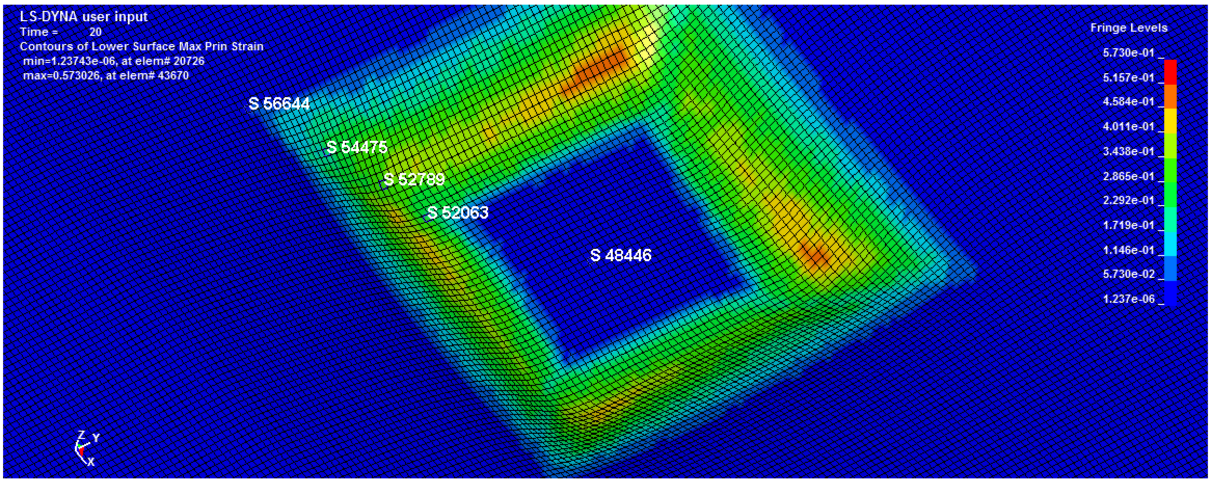


Fig. 4.41 Position of the elements for which there have been studied the variations of the characteristic parameters during forming

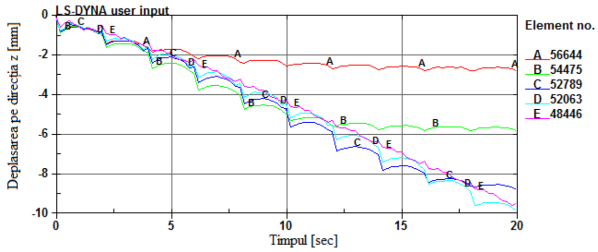


Fig. 4.42 Variation in time of the displacement on the z direction

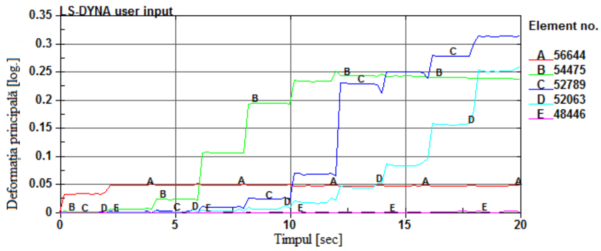


Fig. 4.43 Variation in time of the major strain

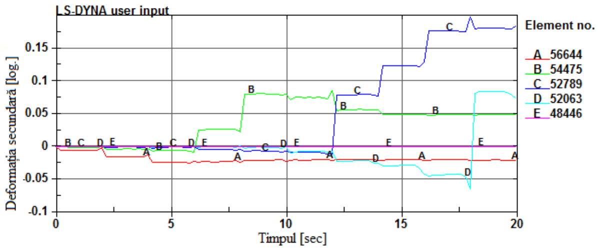


Fig. 4.44 Variation in time of the minor strain

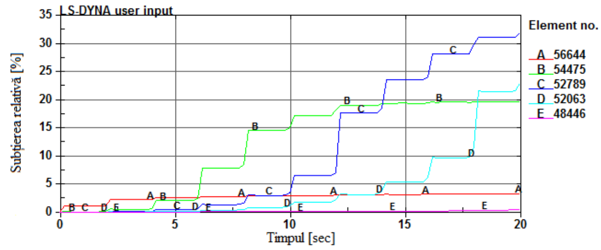


Fig. 4.45 Variation in time of the relative thinning

Figure 4.42 presents the variation in time of the nodal displacement on the five elements. It can be noticed that their variation is similar to that of the nodes from the case of a trajectory describing a cone frustum. The maximal value is presented at the level of the node from the area where the punch realises the last step on vertical direction. The nodes from the part's central area and from the area next to the punch's penetration area, respectively, have values close to the maximal value. In the case of the nodes that are located near the punch's first step penetration area and in the area where the punch realises the first step, it can be noticed that at a given moment, they have constant values, these moments corresponding to the steps where the punch is no longer coming into contact with the material from those areas.

Figure 4.43 presents the variation in time of the major strain. From the graph it can be noticed that the node located next to the penetration area and the node from the part's central area present the smallest strains. The maximal major strains are located at the level of the node from the area where the punch executes the last step.

The variation in time of the minor strain is presented in figure 4.44. From this figure it can be noticed that this parameter has maximal values as in the case of the major strain, in the node from the area where the punch realises the last step. The minimal strains are located in the same nodes as in the case of the major strain.

From figures 4.43 and 4.44 it can be noticed that the strains, just as in the case of the cone frustum, remain constant in value (54475) after the punch has formed the material from this area and continues to form the material from the lower areas (52789, 52063).

The evolution of the values of the material's relative thinning is presented in figure 4.45. Its evolution is similar to that of the major strain, just as in the case of the linear trajectory.

4.5 Determining the forces at the incremental forming

With these analyses it was sought to determine the forces (on the three directions x, y, z and the total force) and the energy consumed during the incremental forming process (the total consumed energy and the Hourglass energy). For this study, there were taken into account three types of trajectories: a trajectory for describing a straight groove with indexing on z at each end, a trajectory for describing a cone frustum and a trajectory for describing a pyramid frustum. Within the simulations, there was used a punch with a diameter of 10 mm, the punch's vertical pitch of 1 mm and as material an aluminium sheet with a thickness of 0.8 mm. For the simulation there has been chosen a model with finite elements in which a blank with a very fine mesh was used. In the following, in this abstract, there will be presented the results obtained for realising a cone frustum.

Cone frustum

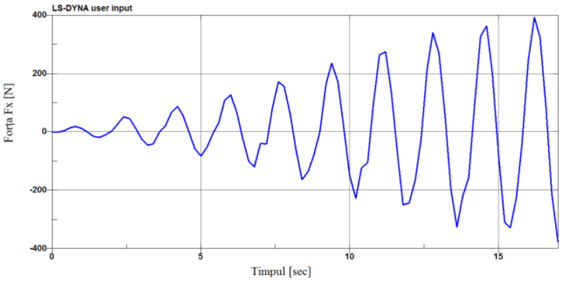


Fig. 4.52 Variation of the component F_x [N] of the force during the forming process

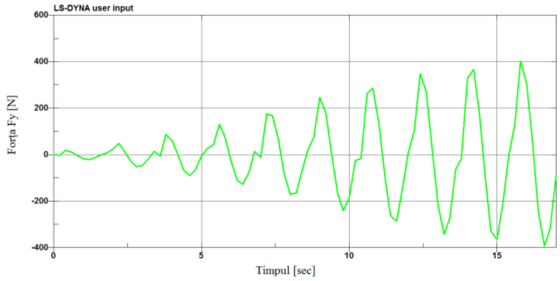


Fig.4.53 Variation of the component F_y [N] of the force during the forming process

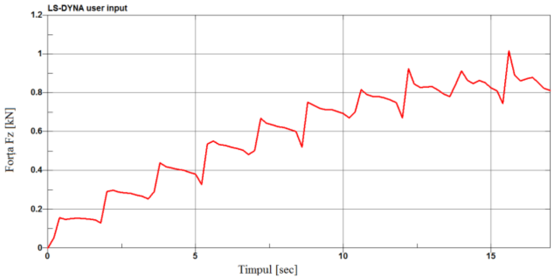


Fig. 4.54 Variation of the component F_z [kN] of the force during the forming process

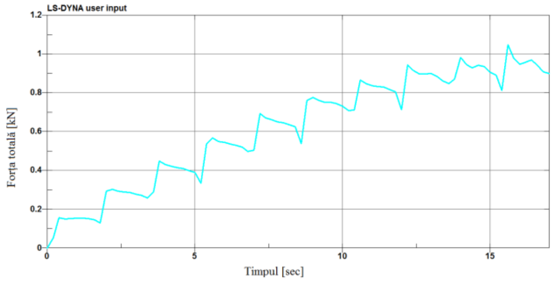


Fig. 4.55 Variation of the forces' resultant, F_R [kN] during the forming process

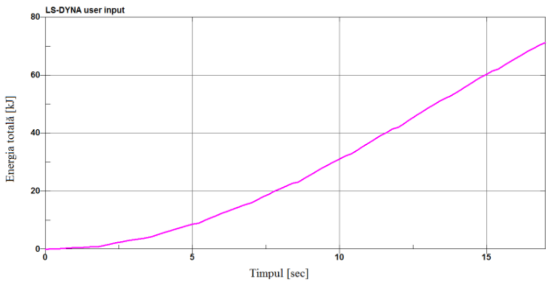


Fig. 4.56 Variation of the total energy [kJ] during the forming process

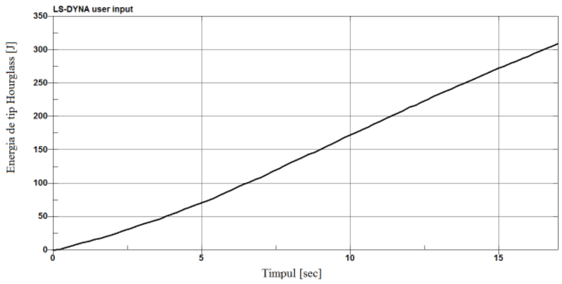


Fig. 4.57 Variation of the Hourglass energy [J] during the forming process

In figures 4.52 – 4.55 there are presented the forces on the three directions z (vertical) and x and y (in the sheet's plane) and the force resulting in the process. From these graphs it can be noticed that as the punch executes circular displacements in the sheet's plane, the forces have a sinusoidal variation shape, a phenoment that is much more pronounced in the case of the forces on x and y directions. When the punch returns to the initial point, just before making a new penetration on z direction, there can be noticed a sudden decrease of the forming force, followed by a sudden increase when the punch penetrates the material anew. This phenomenon is due to the fact that, during the following of a circular trajectory in the sheet's plane, the punch encounters undeformed material, except for the moment when it reaches again the initial point of the displacement in the sheet's plane.

Figure 4.56 presents the total energy consumed while executing a cone frustum type part. As can be seen from the graph, the consumed energy increases at each step, having at the beginning an exponential variation shape and then an approximately linear shape. Figure 4.57 presents the Hourglass energy, which in this case too is much smaller than the total energy consumed during the forming process, so the hourglass-type strains are not influencing the analysis results too much.

4.6 Determining the springback

The analyses presented so far in this chapter were explicit analyses. As opposed to these, the analyses that were run for determining the springback are implicit analyses. An implicit analysis for determining the springback with the ANSYS software is always preceded by an explicit analysis that simulates the analysed forming process. Thus, after running the explicit analysis, all stiff bodies are eliminated from the explicit analysis (in this case: the die, the punch and the blankholder ring), the final part geometry is imported from the explicit analysis and the stresses and strains state from the end of the explicit analysis is imported. The data defining the material's plasticity are eliminated, remaining only those defining its elastic behaviour, i.e. the modulus of elasticity (*E)* and Poisson's ratio (υ), after which the problem is solved using the implicit solvers from the ANSYS 12.0 software. In these analyses, there has been determined the springback for three types of trajectories: a trajectory for describing a straight groove with indexing on z at each end, a trajectory for describing a cone frustum and a trajectory for describing a pyramid frustum. Within the simulations, there was used a punch with a diameter of 10 mm, the punch's vertical pitch of 1 mm and as material an aluminium sheet with a thickness of 0.8 mm.

In the following, in this abstract there are presented the main results obtained for realising a pyramid frustum.

From figure 4.64, it can be noticed that the maximal springback occurs in the area where the punch penetrates on vertical direction. For the rectilinear groove, the minimal springback occurs in the part that is opposed to the first step punch penetration area.

Following these analyses, it can be concluded that, although after these trajectories there should result symmetrical parts, due to the asymmetrical forming pattern and the elastic strains present during the forming, the parts resulting from this forming procedure present a slight asymmetry.

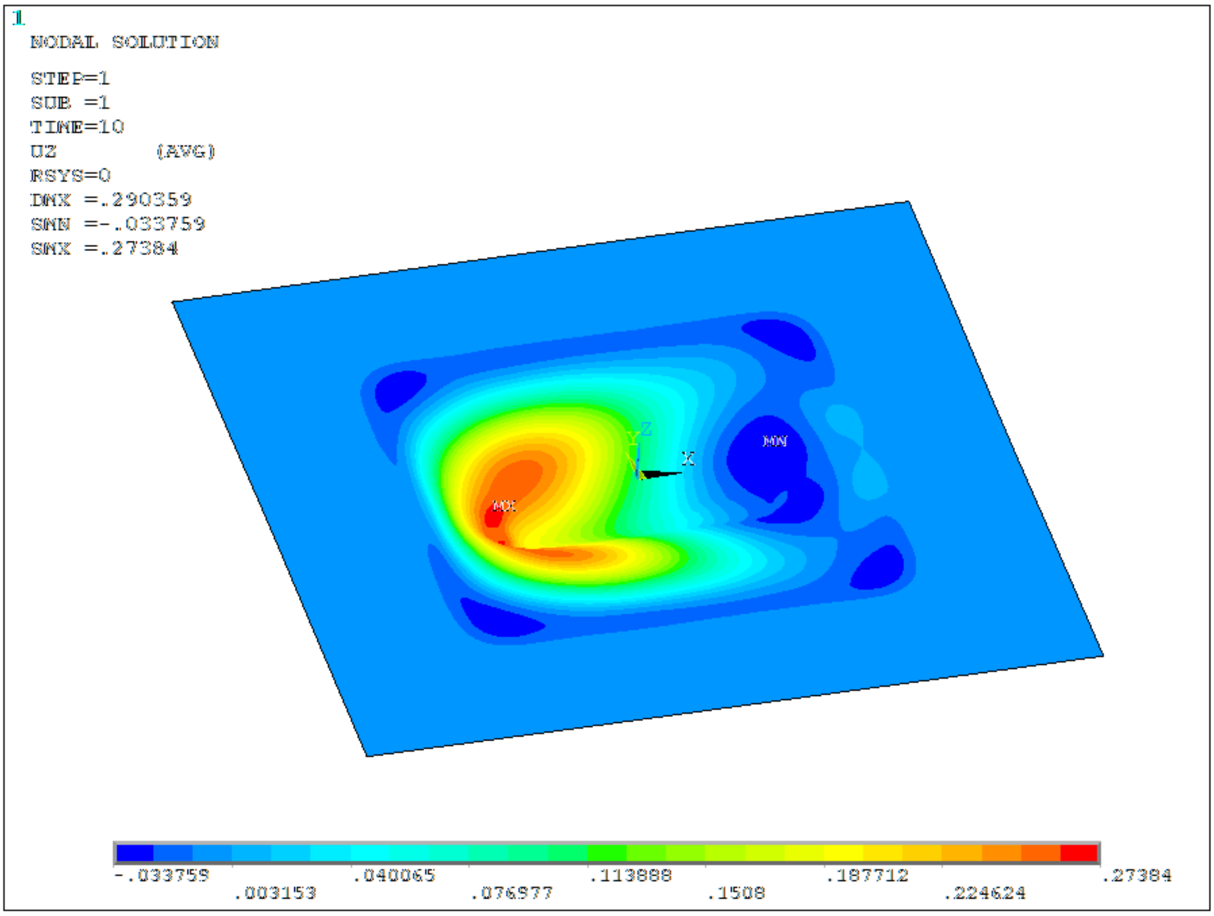


Fig. 4.64 Distribution of the springback on the Oz direction for the rectilinear groove

4.7 Conclusions

For the numerical simulation through MEF of the single point incremental procedure there have been used the software packages Ansys 12.0 şi LS-DYNA. For this, two parametric finite element models were realised.

There have been realised four types of analyses through the finite element method: analyses for determining the influence of geometrical parameters on the strains, analyses for determining the distribution of strains in the part, analyses for determining the forces and analyses for determining the springback. For each type of analysis, three types of trajectories were used: a trajectory for describing a straight groove with indexing on z at each end, a trajectory for describing a cone frustum and a trajectory for describing a pyramid frustum.

5 EXPERIMENTAL RESEARCHES REGARDING THE INCREMENTAL FORMING OF THIN METAL SHEETS

The experimental researches targeted, on the one hand, the determining of the mechanical characteristics of materials, needed for the numerical simulations and on the other hand the validation of the results from the theoretical study concerning the strains occuring the parts and the necessary forming forces. Consequently, there were determined the following objectives:

- determining of the materials' mechanical characteristics through tensile tests;
- determining of the forming limit curves;
- determining of the strains on incrementally formed parts;
- determining of the forces in the incrementally formed parts;
- influence of the geometrical parameters on the strains and forces;
- influence of the forming manner on the strains and forces;
- influence of the geometrical parameters on the part's precision.

5.1 Experimental installations

Depending on the targeted objective, there were used several research installations and equipments, presented in the following.

Tensile testing machine

For determining the mechanical characteristics of materials, there was used a tensile, compression and buckling testing machine Roell & Korthaus RKM 100/20 belonging to the Institute for Metal Forming (Institut für Umformtechnik - IFU) Stuttgart.

Experimental installation for determining the forming limit curves (FLC)

For detemining the forming limit curves there was used the deep drawing installation belonging to the Centre for Metal Forming of the „Lucian Blaga" University of Sibiu and the optical system for measuring strains in real time Aramis.

Optical system for measuring strains - Argus

In order to determine strains in „offline" mode, there was used the optical measuring system Argus, produced by the company GOM. Prior to forming, the test samples were marked electrochemically or with laser.

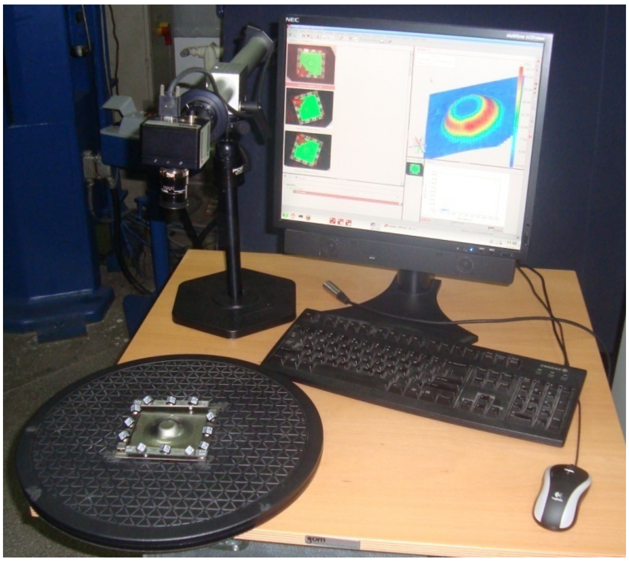
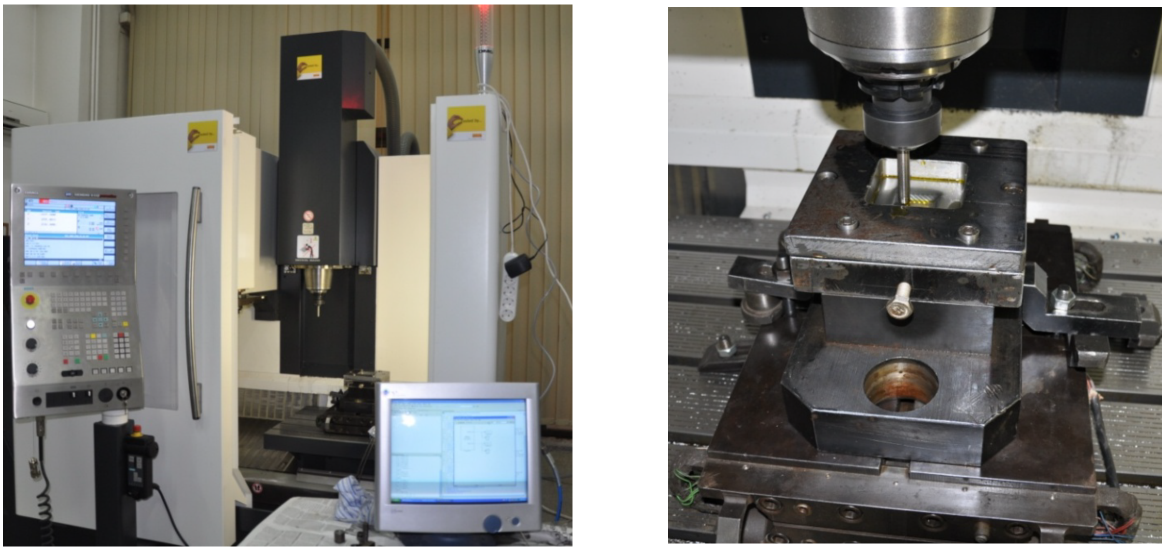


Fig. 5.3 Part during the measurement of strains

Experimental installation for studying the incremental forming process

Because the laboratory does not own a specialised incremental forming machine, the experimental researches were carried out on a numerical controlled milling machine in three axes, capable to describe the complex trajectories traced by the punch for obtaining a part with a certain geometry. There were used two types of milling machines, DMG Veco and Hass, function of the targeted objective and the technical-functional characteristics of the machine.



a) Overview b) Detail with the forming die

Fig. 5.5. Experimental installation using the DMG milling machine

Coordinates measurement machine

In order to determine the precision of parts obtained through the incremental forming procedure, there was used a coordinates measurement machine Contourecord 1600D produced by the company Carl Zeiss and owned by the company S.C. Compa S.A. from Sibiu.

5.2 Determining the mechanical characteristics of materials through tensile testing

The modern computer-aided design software packages offer very good results on the condition that the input data are as precise as possible. Also, the current software programmes for simulating the forming processes allow to introduce material data as curves defined by pairs of points strain – real stress.

The intervals between which the data specific for the plastic flow curve of the material vary are σ_{max}=296.54-325.46 MPa, ε_{max}=44.62-49.54 %, Rp_{02}=163.32-204.59 MPa, n=0.2168-0.2412 and K=488.65-547.016 MPa for steel and σ_{max}=263.39-273.77 MPa, ε_{max}=26.06-28.52 %, Rp_{02}=149.03-166.66 MPa, n=0.2333-0.2584 and K=445.55-457.299 MPa for aluminium.

The material's anisotropy coefficients were determined on the tensile testing machine on test samples extracted at 0°, 45° and 90°.

5.3 Determining of the forming limit curves (FLC)

Forming limit curves are determined experimetally through points of coordinates $\varepsilon_1, \varepsilon_2$, where $\varepsilon_1, \varepsilon_2$ are limit strains, corresponding to a certain loading mode of the test sample (equibiaxial, biaxial, uniaxial etc.). Consequently, in oder to determine a forming limit curve, there need to be realised various loading modes of the material, comprised between the equibiaxial stretching ($\varepsilon_1 = \varepsilon_2$) and pure shearing ($\varepsilon_1 = -\varepsilon_2$) [24].

5.4 Determining of the strains at the single point incremental forming

The main objective of these researches was to determine the distribution of strains in incrementally formed parts. For realising the parts, there were used two types of materials, deep drawing steel type DC04 and aluminium type AA6016, both materials having a good forming behaviour, as can be noticed from the results obtained after carrying out the uniaxial tensile tests and the tests for determining the forming limit curves (CLD).

There were studied:

a) the influence of geometrical parameters on the distribution of strains for:
- a dome shape and a straight groove having as variable factors:
  - the pitch on vertical direction;
  - the punch diameter;
- a pyramid frustum having as variable factors:
  - the pitch on vertical direction;
  - the sloping angle of the part's wall;

b) the influence of the forming manner on the strains for parts of type:
- dome;
- cone frustum;
- pyramid frustum.

The test samples used during the researches have a square shape, with a side length of 120 mm. The punch's feed rate is of 240 mm/min, while the number of rotations is 180 rot/min.

In order to realise parts through the single point incremental forming process, there were used the milling machines, the forming die and the punches presented in chapter 5.1. In annex III, there are presented some types of programmes used for describing the movement of the punch in three axes, for obtaining a certain part. The formed parts were measured using the optical strain measurement system Argus, the measurement of the main strains being done „offline”, after the incremental forming process was finished.

5.4.1 Influence of the geometrical parameters on the distribution of strains

In the following, in the abstract, there are presented the results obtained for realising a dome.

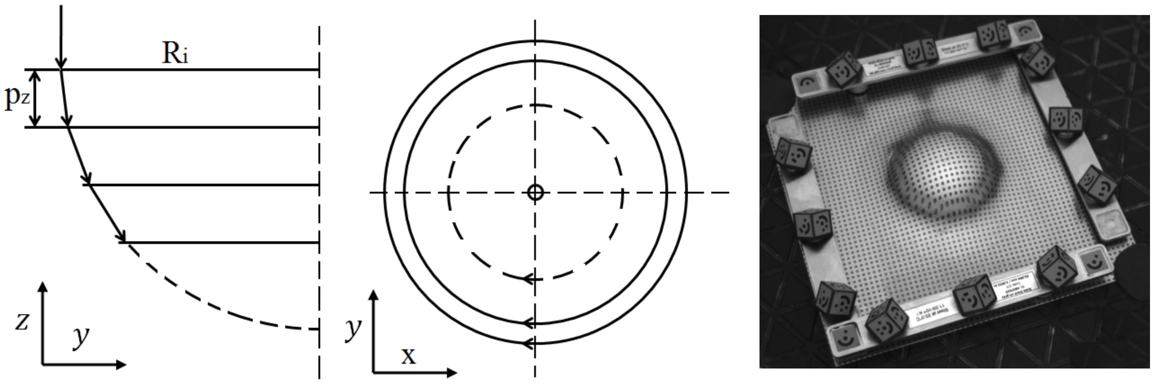
Distribution of the strains and of the relative thinning at the obtaining of a dome

The tests were realised on steel test samples, taking into account two thicknesses: 0.5 and 0.9 mm. There could not be realised tests on aluminium, since it has a lower formability, so it failed during the incremental forming process, the material breaking during forming. Table 5.6 presents the geometrical parameters taken into account and their variation domain.

Table 5.6

Parameter	**Values**	
Punch diameter d_p [mm]	6	10
Pitch on the punch’s vertical direction p_z [mm]	0,25	1

For determining the distribution of strains, there was carried out a set of four tests for each material thickness. The punch trajectories are presented in figure 5.17, a. The punch executes a displacement on vertical direction (z), with a certain constant pitch (p_z), and on y a displacement that is variable function of the radius (R_i). After each displacement in the plane yOz, the punch executes a circular motion of radius R_i in a plane parallel to the sheet’s plane (xOy). The dome realised within this test has the inner radius of 17 mm.



a) b)

Fig. 5.17 a) Trajectories described by the punch b) Dome

The results obtained after the experimental researches are presented in table 5.7.

Maximal values of the main strains and of the relative thinning, as can be seen from the table, are obtained in the cases C1 (for the material of thickness 0.9 mm) and C3 (for the material of thickness 0.5 mm), cases in which there is used a punch of 5 mm diameter and a vertical pitch of 0.25 mm, but at the same time, in these cases there are obtained minimal values for the secondary strains.

The maximal values for the secondary strains are obtained for cases C6 (for the material of thickness 0.9 mm) and C8 (for the material of thickness 0.5 mm), cases in which there is used a punch of 10 mm diameter and a vertical pitch of 1 mm. At the same time, in these cases there are obtained minimal values for the main strains and for the relative thinning for each material thickness.

Table 5.7

Case	**d_p [mm]**	**g [mm]**	**p_z [mm]**	$\varepsilon_{1\ max}$	$\varepsilon_{2\ max}$	***thick***
C1	6	0,9	0,25	0,774	0,0733	0,921
C2	6	0,9	1	0,753	0,152	0,872
C3	6	0,5	0,25	0,956	0,0831	0,972
C4	6	0,5	1	0,875	0,147	0,92
C5	10	0,9	0,25	0,712	0,091	0,794
C6	10	0,9	1	0,649	0,16	0,747
C7	10	0,5	0,25	0,916	0,0944	0,897
C8	10	0,5	1	0,765	0,1508	0,861

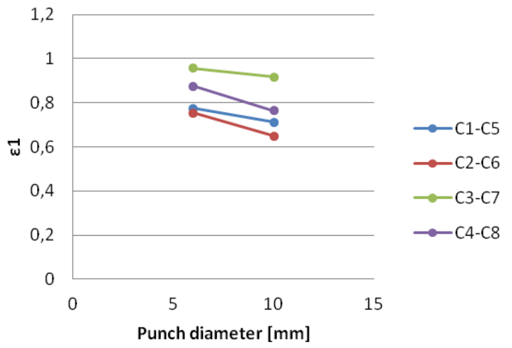


Fig. 5.18 Influence of the punch diameter on the major strain, ε_1

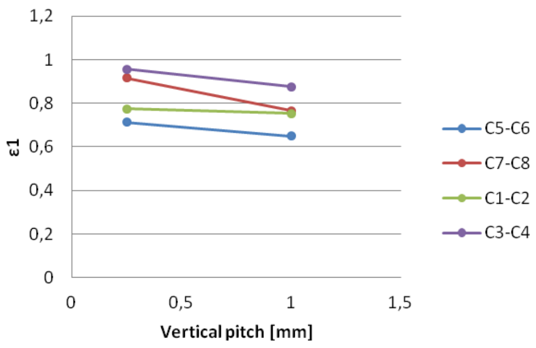


Fig. 5.19 Influence of the pitch on vertical direction on the major strain, ε_1

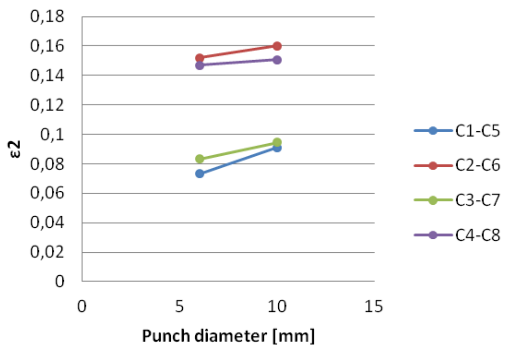


Fig. 5.20 Influence of the punch diameter on the minor strain, ε_2

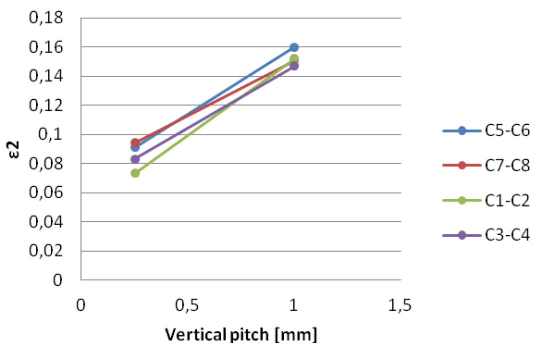


Fig. 5.21 Influence of the pitch on vertical direction on the minor strain, ε_2

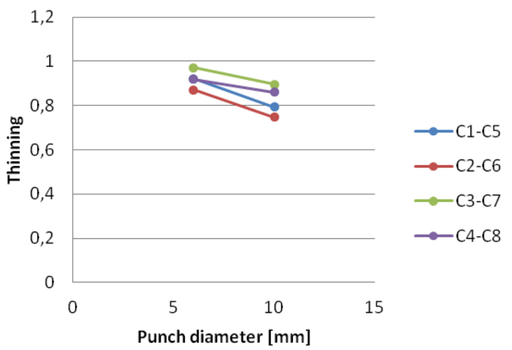


Fig. 5.22 Influence of the punch diameter on the relative thinning

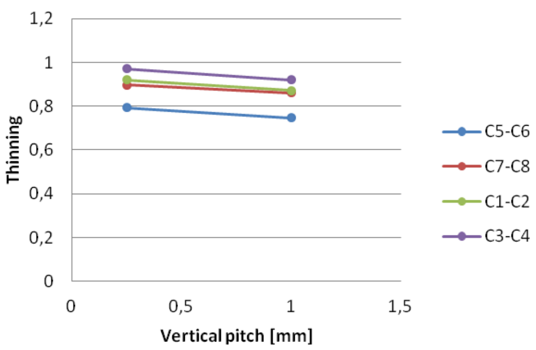


Fig. 5.23 Influence of the pitch on vertical direction on the relative thinning

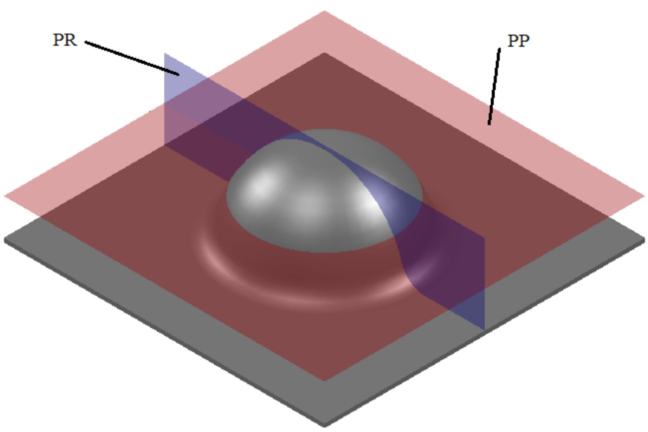
From analysing the table it can be seen that:

- a decrease of the values of the punch diameter leads to
  - a decrease of the values of the minor strain (fig. 5.20)
  - an increase of the major strain (fig. 5.18) and of the relative thinning (fig. 5.22);

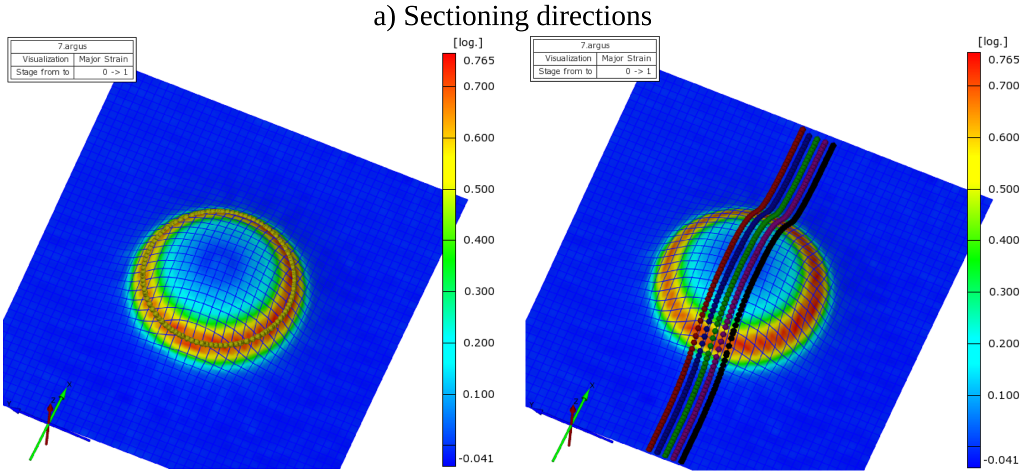
- a decrease of the pitch on vertical direction leads to
  - a decrease of the values of the minor strain (fig. 5.21);
  - an increase of the values of the major strain (fig. 5.19) and of the relative thinning (fig. 5.23).

In order to emphasise the evolution of strains through incrementally formed parts, the dome from case C8 was sectioned on two directions (fig. 5.24): one perpendicular (PP) to the plane xOy, whih intersects the part in two through its centre and a horizontal one, PR (parallel to the plane xOy), found at a distance of 9.5 mm from the undeformed area of the part. On the perpendicular direction, the dome was sectioned with five planes, one coinciding with the vertical plane and the other ones placed symmetrically one one side and the other, at a distance of 2 mm (fig. 5.24, c) while on the horizontal direction, the dome was sectioned with a single plane (fig. 5.24, b).

Figures 5.25 - 5.27 present the distributions of the major strain, of the minor strain and of the relative thinning for the case C8. The measurement manner was presented in subchapter 5.1.



a) Sectioning directions



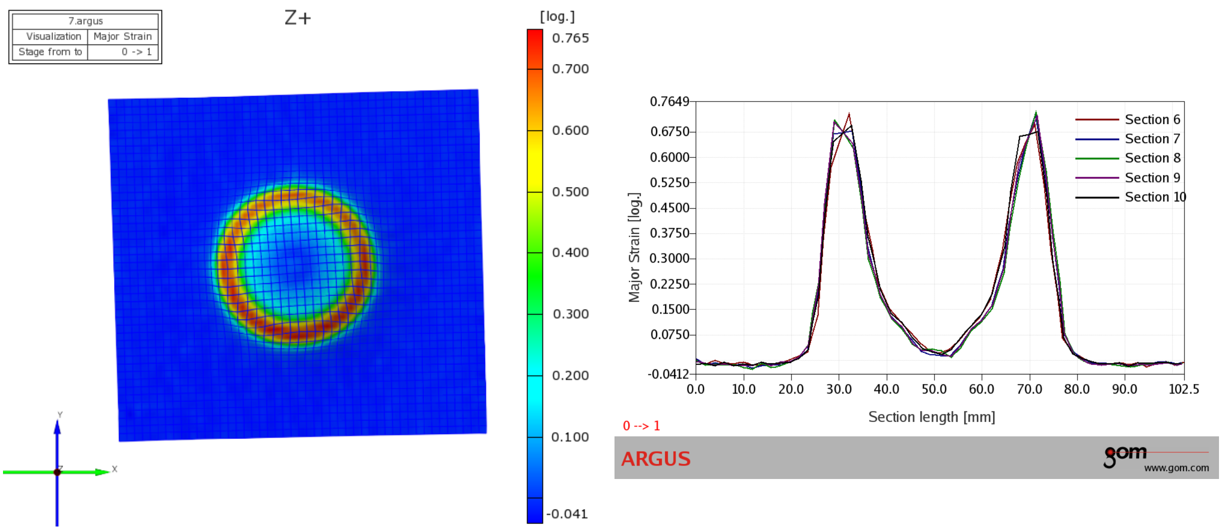
b) Sectionning plane parallel to xOy   c) Sectioning planes perpendicular to xOy

Fig. 5.24 Types of cross-sections through the part

As can be noticed from figure 5.25, a, the major strain varies in the planes parallel to the plane xOy, planes that coincide with the circular movements of the punch. These strains have maximal values in the area where the punch starts its circular motion in the sheet's plane. Their values decrease as the punch moves in the plane.

When analysing the major strain in the plane perpendicular to the plane xOy (fig. 5.25, b), it can be noticed that the value of the major strain is not even and has two local maxima. The values of the major strain decrease towards the dome's top, a fact that is specific for the incremental forming with punch.

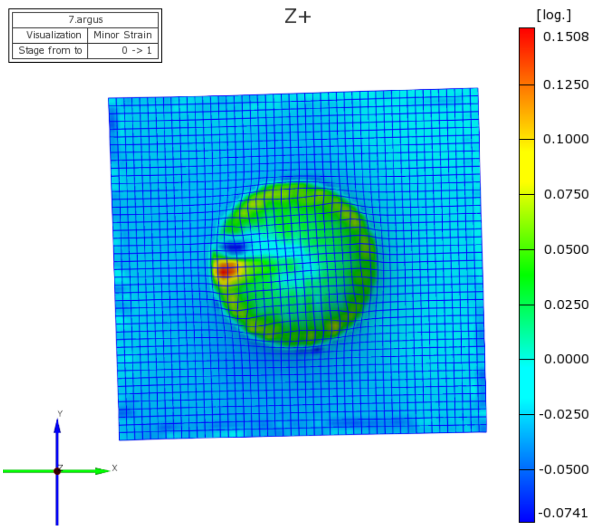
The major strain has maximal values in the forming start area, i.e. in the area in which the punch does the first vertical penetrations and circular feeds. This phenomenon is due to the fact that when executing the first steps, as can be noticed also from figure 5.17, a, the punch has a small displacement on the y direction, which leads to it penetrating into the area of the material deformed previously, thus resulting in larger strains in that area. As the punch progresses, the displacement on y direction increases, so that it ends up forming previously undeformed material areas, leading to smaller strains towards the dome's centre.



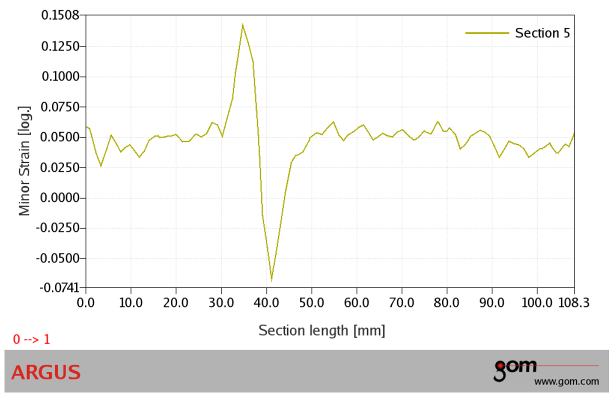
a) Distribution in the part b) Evolution in the perpendicular cross-sections

Fig. 5.25 The major strain

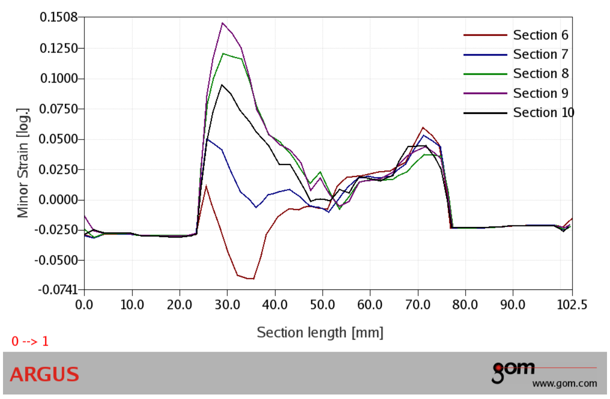
Figure 5.26 presents the variation of the minor strain. The figure shows that it has maximal values in the area in which the punch penetrates vertically at each step. The minor strain has minimal values in the moment when the punch returns in the initial position, after going through the circular trajectory. In this area, there are smaller minor strains because during the displacement in the plane xOy, in front of the punch there accumulates material but, towards the end of the circular trajectory, when the punch nears the area that was formed at the beginning, it does not encounter anymore a resistance to forming. This is emphasised also in figure 5.26, b where an increase in the value of the minor strain can be noticed at the moment of executing the vertical penetration, but also at the end of the circular motion, when a sudden decrease of the value can be noticed. The phenomenon occurs also in the vertical cross-sections, figura 5.26, c.



a) Distribution in the part



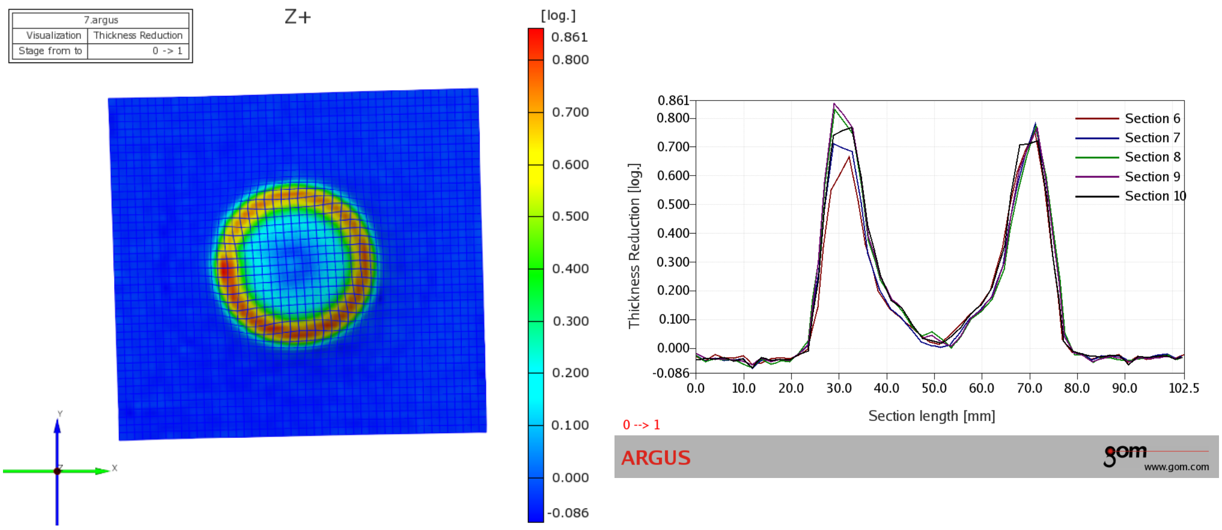
b) Evolution in the parallel cross-section



c) Evolution in the perpendicular cross-sections

Fig. 5.26 The minor strain

The variation of the relative thinning for this case is presented in figure 5.27. This has the same variation pattern as the major strain. It has maximal values in the penetration areas and as the punch executes the circular trajectories, its values decrease.



a) Distribution in the part b) Evolution in the perpendicular cross-sections

Fig. 5.27 Relative thinning

5.4.2 In the following, in the abstract there will be presented the results obtained during the realising of a dome

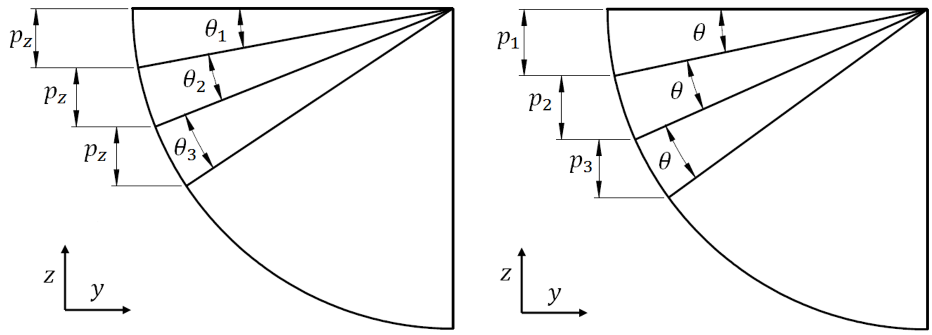
In the following, in the abstract there will be presented the results obtained during the realising of a dome.

Distribution of the strains and of the relative thinning at the obtaining of a dome

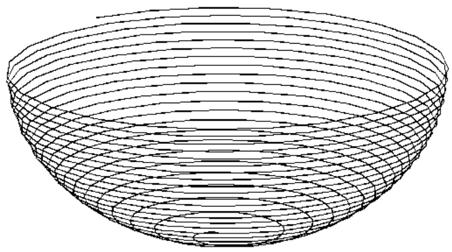
The main objective of these researches consisted in determining the optimal forming manner, so that the dome realised by single point incremental forming has an distribution of the strains that is as even as possible and the relative thinning is minimal. For realising the parts, there have been used steel test samples with a thickness of 0.7 mm and a punch with a diameter of 8 mm. The obtained domes have an inner radius of 19 mm.

The trajectory of the forming tool is very important for the obtaining of the parts by incremental forming and therefore there have been chosen, for realising the dome-shaped parts, three trajectory variants, depicted in figure 5.50.

Variant V1: This trajectory is defined by the fact that the pitch on vertical direction (z direction), has a constant value p_z = 1 mm throughout the duration of the forming procedure. The starting point of the punch is on the circle with the maxima diameter. After executing a full circle (360°), the punch penetrates with one step that remains constant on vertical direction (pz) producing an angle in the xOz plane whose value (θ_i) changes with each step, as can be seen in figure 5.50, a. This leads actually to a displacement of the punch on a circle in horizontal plane, whose radius changes with every step realised on vertical direction. The punch's movement repeats until the whole part geometry is defined. It should also be noted that the punch keeps its vertical position throughout the forming process.



a) Constant pitch on z b) Constant angular pitch



c) Loxodrome

Fig. 5. 50 Trajectories of the punch for obtaining a dome

Variant V2: This trajectory is defined by the fact that the penetration angle of the punch in the plane yOz (θ), has a constant value, throughout the duration of the forming process. The starting point of the punch is found here too on the circle with the maximal diameter. After executing a full circle (360°), the punch penetrates under an angle $\theta = 6°$ and with a vertical step that changes after executing each circular trajectory ($p_{z.i}$), as can be noticed in figure 5.50, b. This leads in this case too to a displacement of the punch on a circle in a horizontal plane whose radius changes with each step executed on vertical direction.

Variant V3: This trajectory is actually a loxodrome trajectory (fig. 5.50, c). The punch has the same starting point as with the other two types of trajectories. The characteristic of the loxodrome trajectory is that it intersects all meridians of a spherical body under the same angle. The pitch between two successive trajectories was in this case $p_z = 1$ mm. Basically, the punch executes a continuous penetration in the material on all three directions. In this case too, the punch keeps a vertical position to the initial sheet plane throughout the forming process.

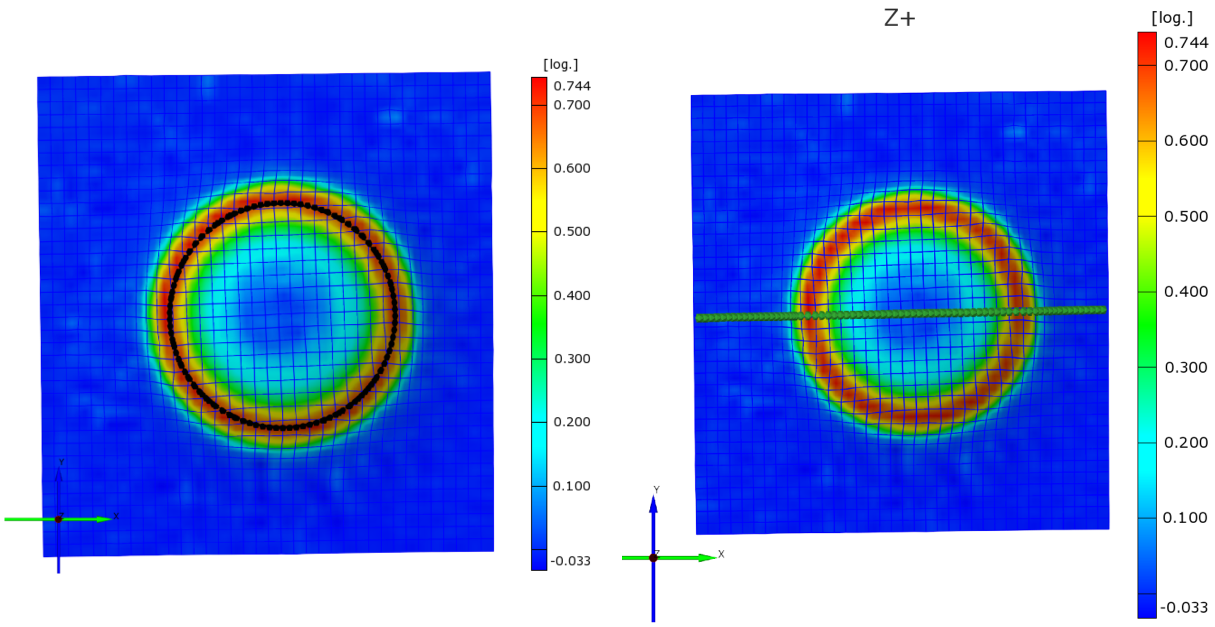
For all three trajectories, the punch's movement is realised in clockwise direction.

Table 5.11 presents the results obtained after measuring the main strains and the relative thinning for the three types of trajectories.

Table 5.11

Variant	$\varepsilon_{1\ max}$	$\varepsilon_{2\ max}$	***Thinning***
V1	0,78	0,234	1,001
V2	0,8	0,1698	0,953
V3	0,744	0,1067	0,806

It is noteworthy that, as opposed to other forming procedures, the variation of the main strains and of the relative thinning at the single point incremental forming is directly linked to the trajectory followed by the punch during the part's processing. In order to show this, the dome-shaped part was cross-sectioned by two planes: one perpendicular (PP) to the plane xOy that cuts the part in two through its middle and a horizontal one (PR), (parallel to the plane xOy) that is found at a distance of 9.5 mm to the undeformed area of the part, as can be seen in figure 5.51.



a) Cross-section parallel to xOy b) Cross-section perpendicular on xOy

Fig. 5. 51 Types of sections through the part

As can be seen, for all three types of trajectories, the major strain and the relative thinning have maximal values along a curve situated in a plane parallel to xOy, similarly to the strains obtained in parts tested through the Erichsen method. This curve corresponds to a circular punch trajectory placed towards the middle of the part (at a depth of approximately 9-10 mm). The values of the main strains and of the relative thinning decrease towards the dome's top, a fact that is specific for the incremental forming with punch.

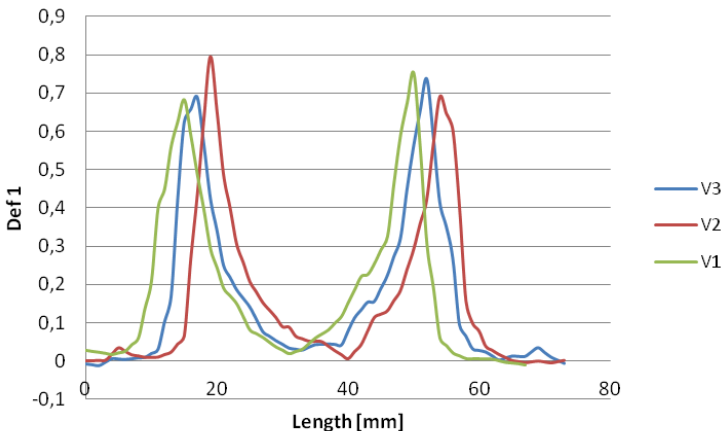
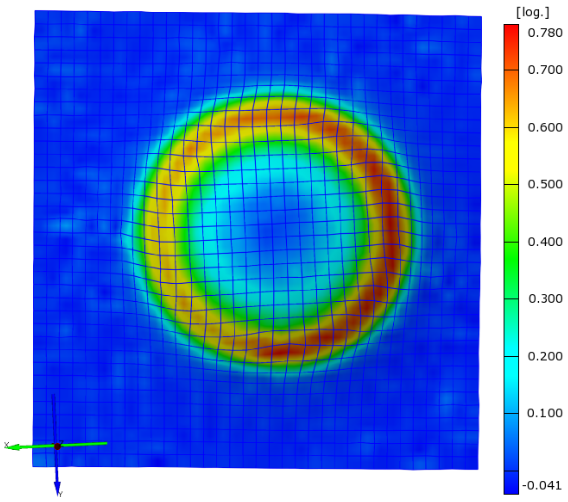


Fig. 5. 52 Major strain - perpendicular cross-sections

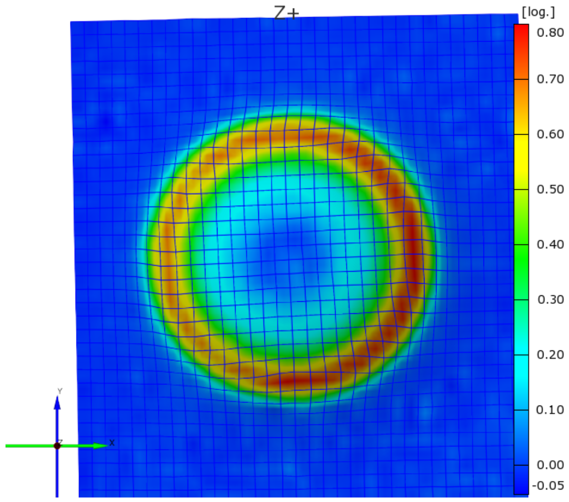
When analysing the strain in a plane that is perpendicular on the plane xOy (fig. 5.52), it can be noticed that the value of the major strain is not even in the cross-section PP, presenting two local maxima.

Even so, both for the trajectory with constant pitch (V1) and for the trajectory with constant angle (V2) it can be noticed that the value of the major strain does not maintain an even variation on the same circular trajectory. Thus, the maximal value of the major strain is always found in the initial penetration point of the punch on vertical direction (first vertical step), after which this value decreases progressively until the end of the circular trajectory located in the same plane (fig. 5.53, a şi 5.53, b). As opposed to the first two variants, in the case of the loxodrome trajectory (V3) the values of the major strain are relatively constant on the same circular trajectory, as can be seen from figure 5.53, c.

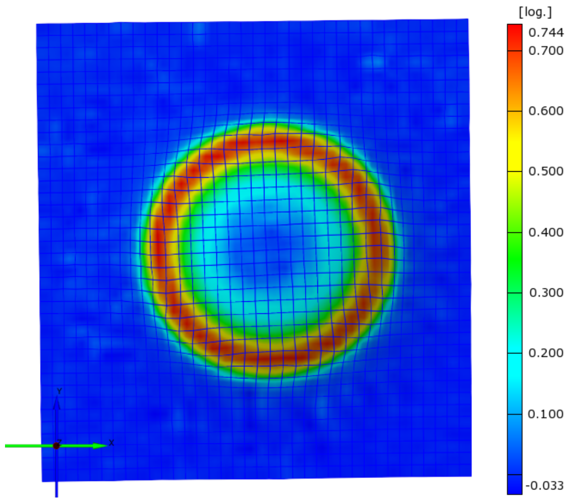
With regard to the values of the major strains, the maximal value of 0.8 occurs in the case of the trajectory with constant angle (V2). In the case of the trajectory with constant pitch (V1), the maximal value of the major strain is of 0.78. The smallest value among the obtained maximal values is found with the loxodrome trajectory (V3), the value of the major strain being of 0.744.



a) V1



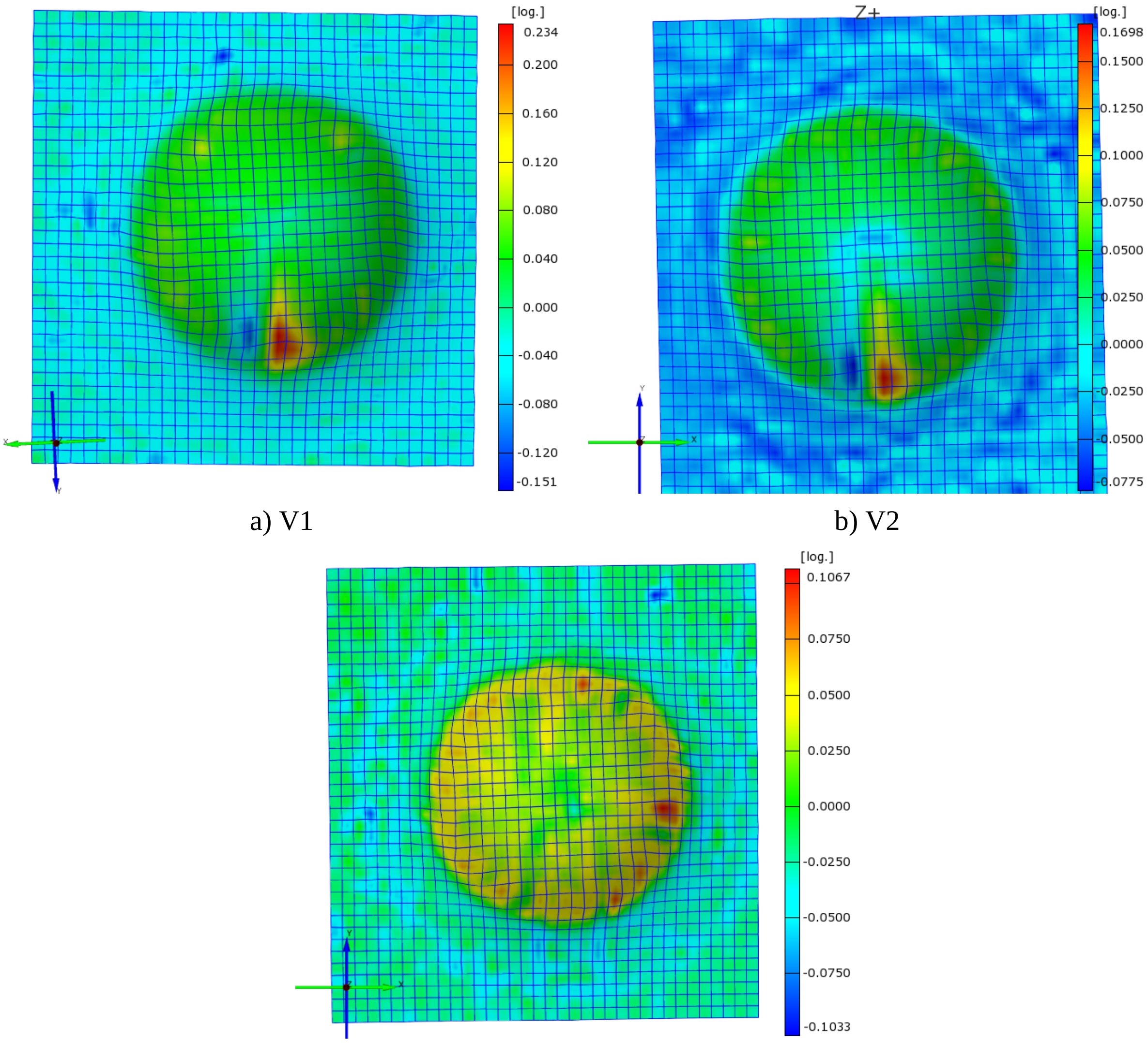
b) V2



c) V3

Fig. 5. 53 The major strain - distribution through the part

The minor strain has a maximum also in the initial penetration point of the punch on vertical direction for all three trajectory types (fig. 5.54). If in the case of the loxodrome trajectory (V3), the value of the minor strain is relatively constant on the rest of the dome surface, for the other two types of trajectories (V1 and V2) it can be noticed also from figure 5.55 that towards the end of the circular trajectory the minor strain decreases sharply, leading to negative values for it. This is due to a wrinkle of material that rises in front of the punch for these two types of trajectories. Basically, in that area, there occurs a compression loading of the material. In the case of the loxodrome trajectory (V3), where the process is unfolded continuously, without repeated penetrations of the punch on vertical and circular direction, this material wrinkle does not occur. The material's wrinkling in the area in front of the punch represents a major disadvantage of the two types of trajectories (V1 şi V2), also leading to a decrease of the precision of the obtained parts. The maximal values obtained for the minor strain are of 0.234 for the trajectory with constant pitch (V1), 0.1698 for the trajectory with constant angle (V2) and 0.1067 for the loxodrome trajectory (V3), respectively.



a) V1 b) V2

c) V3

Fig. 5.54 Minor strain – distribution through the part

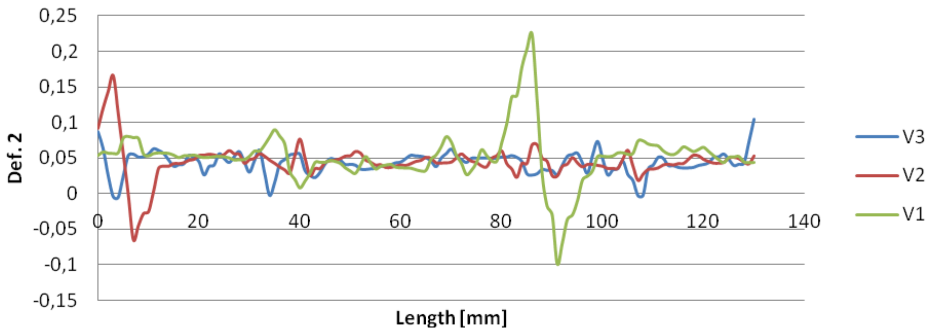
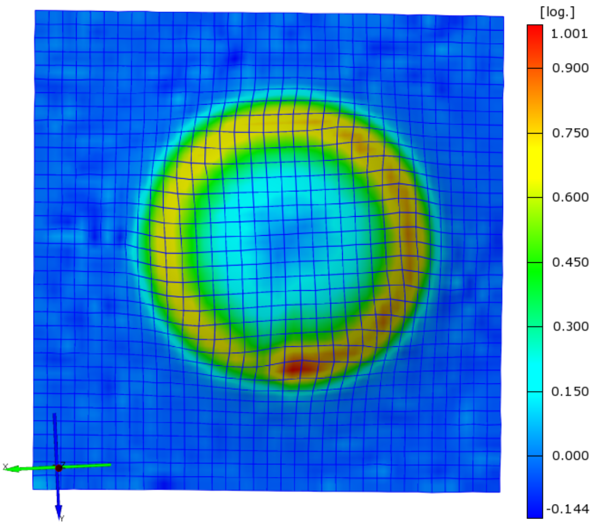


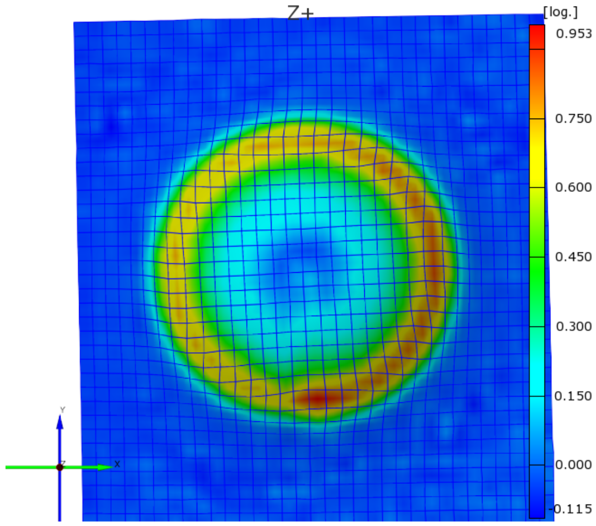
Fig. 5.55 Minor strain - parallel cross-sections

The relative thinning has a similar variation to the one of the major strain for all three types of trajectories. The maximal values is obtained in the initial penetration point of the punch on vertical direction, the larger values being placed similarly to the case of the major strains and they decrease with the decreasing of the diameter of the circular trajectory (fig. 5.56). The maximal values obtained for the relative thinning are of 1.001 for the trajectory with constant pitch (V1), 0.953 for the trajectory with constant angle (V2) and of 0.806 for the loxodrome trajectory (V3).

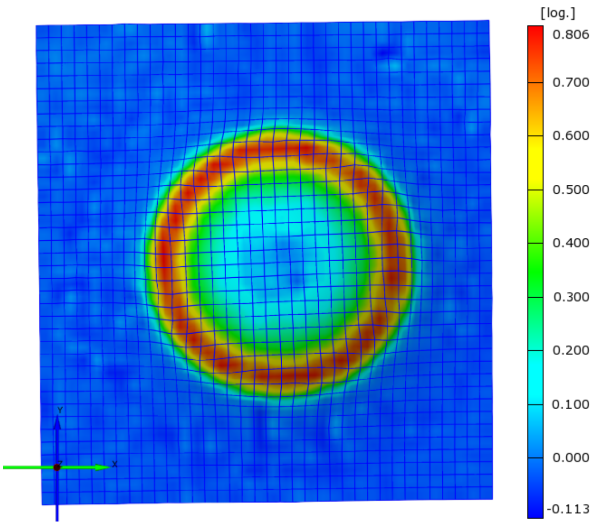
In conclusion, from the point of view of the main strains and of the relative thinning, it can be said that the variant with a loxodrome trajectory is the best because it leads to constant strains and relative thinnings, but also to lower values for these parameters.



a) V1



b) V2



c) V3

Fig. 5.56 Relative thinning – distribution through the part

5.5 Determining the forces at the single point incremental forming

The main objective of these researches consisted in determining the forces resulted from the single point incremental forming process, because this procedure is a complex one and as opposed to other forming processes, such as deep drawing. the forming tool executes a spatial motion on all three axes of the coordinates system, simultaneously or successively, function of the type of trajectory described by the punch.

The studied elements included the variation manner of the forces function of the part geometry, the influence of geometrical parameters and of the forming manner on the variation pattern and the value of the forces. For this, the forces have been measured on the same parts that were used also for determining the strains. In the case of determining the forces, their values were measured online, during the single point incremental forming process, by means of tensometric transducers assembled in bridges on the rings of the dynamometric table.

There has been studied:

a) the influence of geometrical parameters on the forces for:
- dome, straight groove and cone frustum, having as variable factors:
    - the pitch on vertical direction;
    - the punch diameter;
- pyramid frustum, having as variable factors:
    - the pitch on vertical direction;
    - the sloping angle of the part's wall;

b) the influence of the forming manner on the forces for:
- dome;
- cone frustum;
- pyramid frustum.

5.5.1 Influence of the geometrical parameters on the forces

In the following, in the abstract, there are presented the results obtained for realising a dome.

Variation of the forces for the obtaining of a dome

The tests were carried out on steel sheets with two thicknesses: 0.5 and 0.9 mm. Table 5.6 presents the geometrical parameters taken into account and their variation domain.

The trajectories for obtaining the dome-shaped parts are the same as for measuring the strains and are presented in subchapter 5.4, figure 5.17, a. Table 5.14 presents the results obtained following the measuring of forces on two directions of the coordinates axes, x and z.

When analysing the table 5.14 it can be seen that for both material thicknesses, the maximal values for the forces, on both directions, are obtained in the cases C8 and C7, with a punch of diameter 10 mm and with a vertical pitch of 1 mm, while the minimal values for the forces, on both directions, are obtained in the cases C2 and C1, with a punch of diameter 6 mm and with a vertical pitch of 0.25 mm. This emphasises the fact that the decrease of the values of the punch diameter and the decrease of the vertical pitch lead to a decrease of the value of the forces on both directions. The variation manner is presented in figures 5.74 - 5.77.

Table 5.14

Case	**d_p [mm]**	**p_z [mm]**	**g [mm]**	**F_{xmax} [N]**	**F_{zmax} [N]**
C1	6	0,25	0,5	98,588	256,76
C2	6	0,25	0,9	252,84	1032,92
C3	6	1	0,5	224,28	425,18
C4	6	1	0,9	529,48	1446,9
C5	10	0,25	0,5	141,344	364
C6	10	0,25	0,9	375,06	1187,76
C7	10	1	0,5	306,18	841,26
C8	10	1	0,9	616,84	1726,2

Figure 5.78 presents the variantion graphs of the forces on the two directions, x and z, for case C8. From figure 5.78, b it can be seen noticed that the forces on x direction, in the sheet's plane, have the same variation for each circular motion. At each penetration of the punch there occurs a local maximum and at each end of a circular motion in the sheet's plane there is a sudden decrease. Figure 5.78, a presents the variation graph for the forces on vertical direction, i.e. on z. Just as in the case of the forces on the x direction, from the sheet's plane, the force on vertical direction has a sinusoidal variation for each displacement in the sheet's plane, local maxima at the

moment of the punch's movement on z direction and minima at the final moment of each plane circular motion.

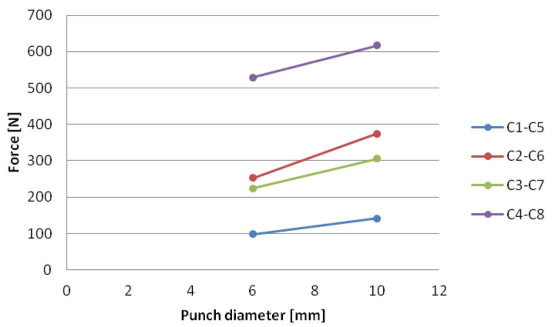


Fig. 5.74 Influence of the punch diameter on the force F_x

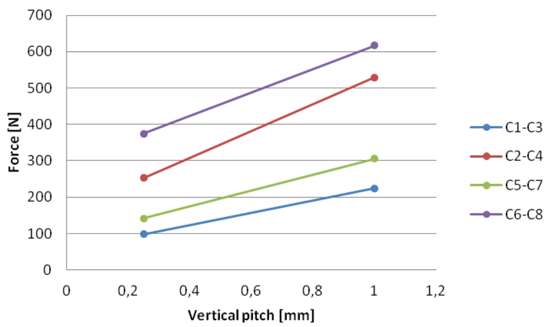


Fig. 5.75 Influence of the pitch on vertical direction on the force F_x

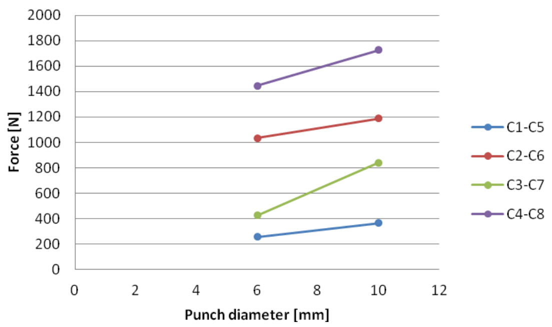


Fig. 5.76 Influence of the punch diameter on the force F_z

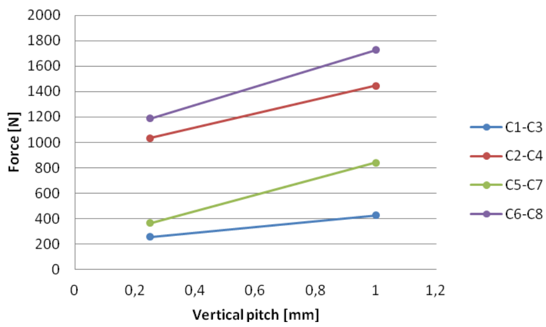
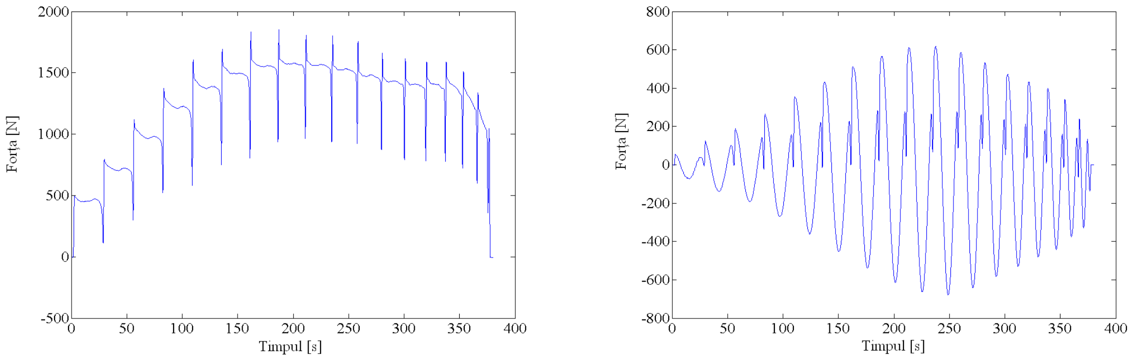


Fig. 5.77 Influence of the pitch on vertical direction on the force F_z



a) F_z b) F_x

Fig. 5.78 Forces for the case C8

5.5.2 The influence of the forming mode on the forces

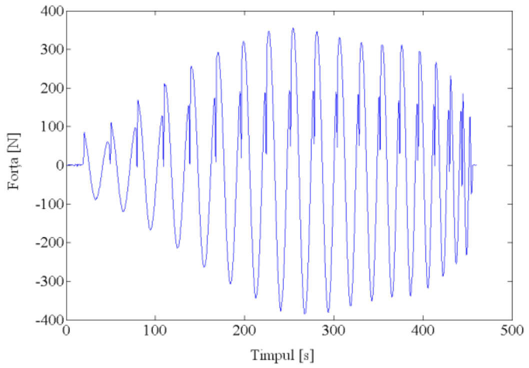
The main objective of these researches was to determine experimentally the variation mode of the forces when various trajectories for the punch displacement are defined in order to obtain parts with different shapes. The obtained shapes and the employed trajectories are identical with those used for the analysis of the strains. The tests were carried out on samples of DC04 deep drawing steel, with a thickness of 0.7 mm and using as forming tool a punch with a diameter of 8 mm. In the following, in the abstract, there are presented the results obtained for the realising of a dome.

Variation of the forces at the obtaining of a dome

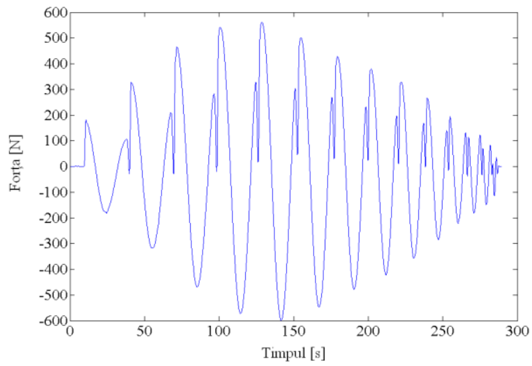
Table 5.18 presents the results obtained after measuring the forces on the two directions of the coordinates system, Ox and Oz.

Table 5.18

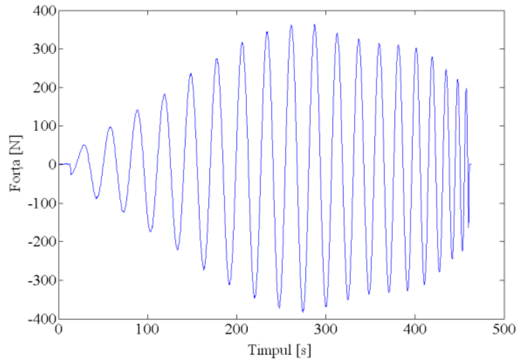
Variant	**F_{xmax} [N]**	**F_{zmax} [N]**
V1	355,6	871
V2	562,5	1265
V3	364,2	768



a) V1



b) V2



c) V3

Fig. 5.97 Forces on the x direction

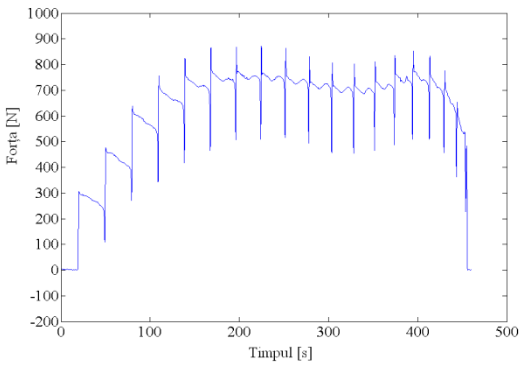
Concerning the variation of the forces, as has been shown, the force component on vertical direction has a much larger value than the components in the sheet's plane, in all three trajectory variants. In this thesis there are presented the variations of the vertical component and of one horizontal component (the component on x direction), the other horizontal component (the component on y direction) having a similar variation. With regard to the values of the force on horizontal direction (Fx) it can be seen that the maximal value of 562.5 N occurs in the case of the constant angle trajectory (V2). In the case of the loxodrome trajectory (V3), the maximal value of the force on x direction is of 364.2 N. The smallest value among the maximal values obtained is found for the trajectory with constant pitch (V1), its value being of 355.6 N. The value obtained in the case of the loxodrome trajectory is, however, very close to the latter one.

Both in the case of the trajectory with constant pitch (V1) and in the case of the trajectory with constant angle (V2), the variation of the force component on horizontal direction has a harmonic variation with variable amplitude. It can be noticed that the amplitude increases almost linearly until the moment when the maximum is obtained. The maximal value of the force, for both types of trajectories, is obtained at the moment when the punch follows the circular trajectory on which the maximal values for the major strain and the relative thinning are found, trajectory that is located at about half the total height of the part. In the case of the variant with constant pitch, after reaching the maximum, the amplitude decreases after a curve that also has a point of local maximum, while in the case of the trajectory with constant angle, the amplitude decreases linearly until the whole surface is realised. With regard to the variation of the component Fx for the first two types of trajectories, it can be said that at each penetration of the punch there occurs a local maximum, while at each end of a circular trajectory, a sudden decrease of the value occurs.

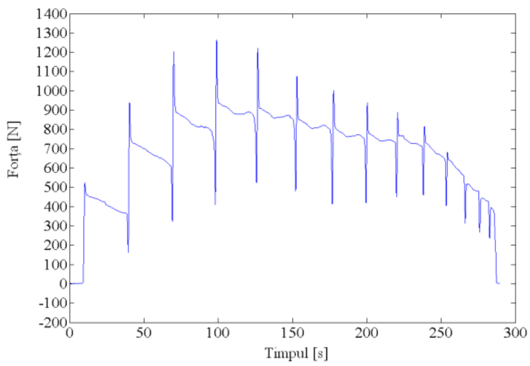
With regard to the loxodrome trajectory, the variation of the component Fx also presents a continuous harmonic variation with variable amplitude, but without sudden decreases or increases of the value. In this case too, there can be noticed an increase of the amplitude until the reaching of the maximal value of the horizontal component (also at the moment of realising the trajectory with maximal strains and relative thinnings).

In conclusion, even if the value of the force component on horizontal direction, Fx, is slightly smaller in the case of the trajectory with constant pitch (V1) than in the case of the loxodrome trajectory (V3), from the force variation it can be seen that in the case of the loxodrome trajectory, it is much smoother, without shocks, being thus less stressing for the feed system of the milling machine. Figure 5.97 presents the graphs obtained for the horizontal component of the force (Fx) for all three trajectory types.

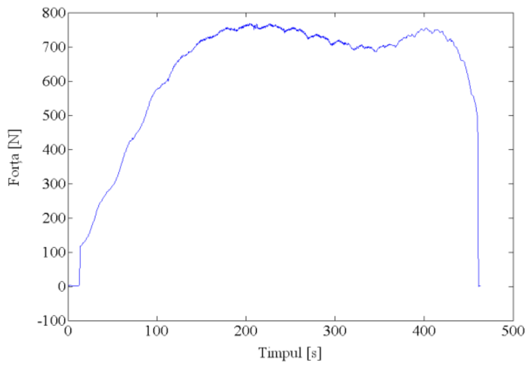
With regard to the values of the force on vertical direction (Fz) it can be seen that the maximal value of 1265 N occurs in the case of the trajectory with constant angle (V2). In the case of the trajectory with constant pitch (V1), the maximal value of the force on z direction is of 871 N. The smallest of the maximal values obtained is found in the case of the loxodrome trajectory (V3), its value being of 768 N. It can be seen that the loxodrome trajectory leads to forces whose maximal value is sensibly lower than in the case of the other two types of trajectories. In the case of the trajectory with constant pitch (V1), the variation of the vertical force component has a local maximum after each penetration of the punch on vertical direction, followed by a sudden decrease and then by a slow decrease until the end of a circular trajectory, when there is again a local minimum. This variation repeats until reaching the maximal value of the force on vertical direction. This maximum is reached at about one third of the total height of the part. It can be noticed that the differences between the local maxima and minima of each circular trajectories remain approximately constant throughout the whole trajectory.



a) V1



b) V2



c) V3

Fig. 5.98 Forces on the z direction

In the case of the trajectory with constant angle (V2), the variation of the vertical force component is similar to the one from the case of the trajectory V1, except for the fact that the differences between the local maxima and minima of each circular trajectory decrease, in this case, significantly after reaching the maximal value of the component Fz. Also, the decreasing shape of the curve has a plane portion in the case of the V1 trajectory, being similar to the case of the Fx component.

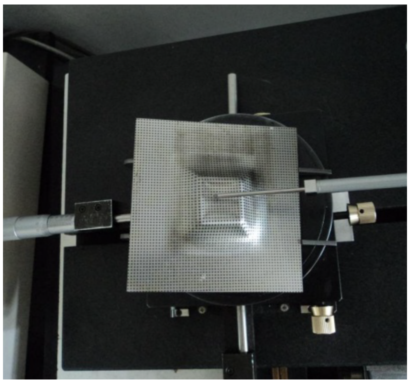
In the case of the loxodrome trajectory (V3), the variation of the vertical force component is smooth, without local maxima or minima. The vertical component of the force increases until reaching the maximal value (again at approximately half the part's height) after which it remains on a relatively constant plane until almost the end of the part's processing. It can be seen that, in all three cases, the value of the vertical force component (Fz) decreases towards the end of the part's processing due to the part's shape (dome), which leads to a reduced area needing to be formed towards the trajectory's end. Figure 5.98 presents the graphs obtained for the vertical force component (Fz) for all three types of trajectories. As in the case of the horizontal components, it can be seen that the optimal variant for processing is the one with a loxodrome trajectory, which has smaller maximal values and a smooth variation.

5.6 Determining of the geometrical precision

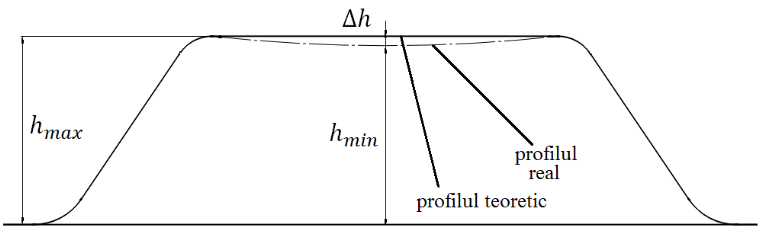
The main objective of these researches consisted in determining the shape precision of the incrementally formed parts, for which reason a pyramid frustum type part was chosen. The analysed parts are identical with the ones used for determining the strains and forces.

The author studied the influence on the part's precision of following factors:

- pitch on vertical direction;
- sloping angle of the part's wall.



a) The part



b) The measured profiles

Fig. 5.103 Measuring the precision

Using the coordinate measuring machine Contourecord 1600D, there were determined the level variations Δh of the part's bottom from the theoretical profile (fig. 5.103). These variations have been analysed both along the sides of the part's bottom (direction A-B and direction A-C) and along the diagonal of the part's bottom (direction A-D) (fig. 5.104). Points A, B, C and D are the points where maximal and minimal values of the part's height were recorded.

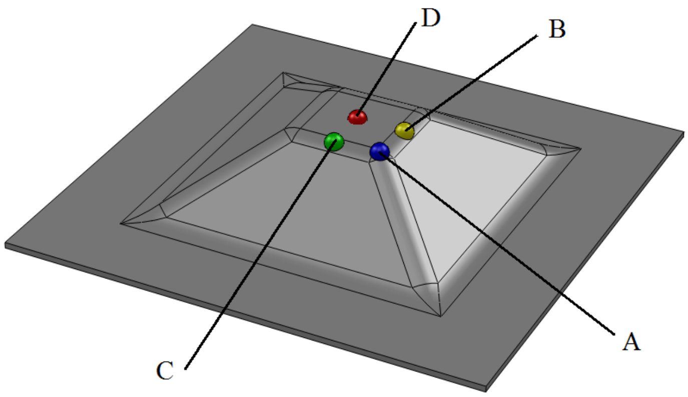


Fig. 5.104 Directions for measuring the part

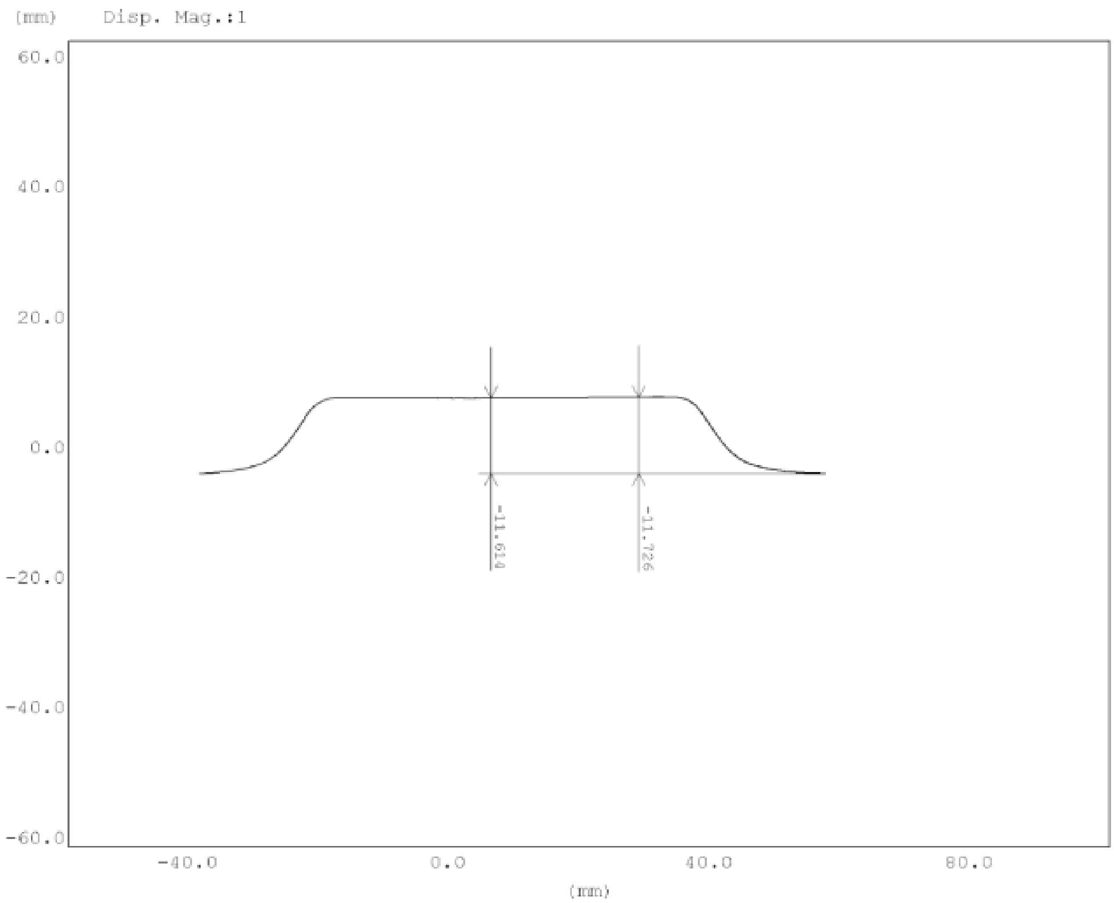


Fig. 5.105 Part profile for case C3

In all analysed cases, the maximal level difference occurs at the middle of the part (in point D). Taking into account that the values recorded on the directions A-B and A-C do not differ significantly and have lower values than those measured on the A-D direction, the analysis considered only the values from this direction. Table 5.21 presents the results of the experiments.

Table 5.21

Case	p_z [mm]	u_g [°]	$\Delta h_{A\text{-}D}$ [mm]
C1	2	65	0,425
C2	1	65	0,22
C3	0,25	65	0,112
C4	2	55	0,731
C5	1	55	0,523
C6	0,25	55	0,178
C7	2	45	0,864
C8	1	45	0,651
C9	0,25	45	0,231

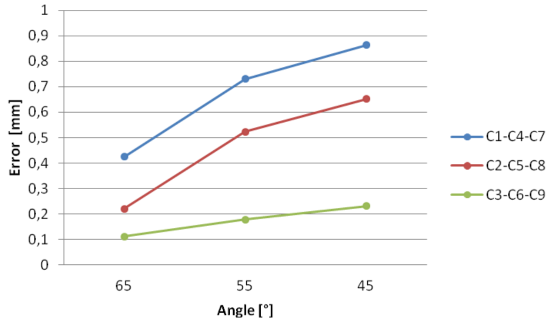


Fig. 5.106 Influence of the part's angle on the precision

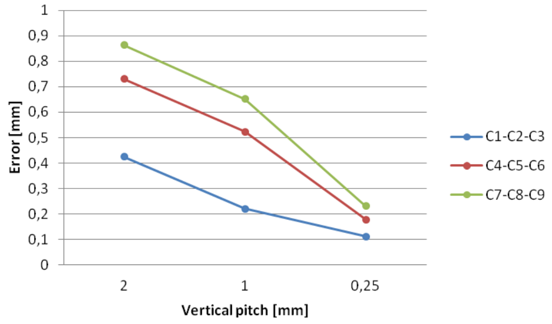


Fig. 5.107 Influence of the vertical pitch on the precision

As can be seen from the table, the increase of the sloping angle of the part leads to a decrease of the value of the level difference (Δh), while the increase of the vertical pitch leads to an increase of this difference (fig. 5.106 and 5.107).

In conclusion, in order to obtain a level difference on the part's bottom that is as small as possible, it is recommended to use large sloping angles for the part's wall and vertical pitches that are as small as possible within certain limits, because by increaseing the angle, the strains increase too, so there is a risk of fissures or even fractures occuring.

5.7 Conclusions

The main objective of these researches consisted in determining the distribution of strains in the incrementally formed parts and in determining the process forces on two directions, one vertical and one in the sheet's plane. For realising the parts, there have been used two material types, a deep drawing steel DC04 and an aluminium AA6016, materials with a good formability.

With the help of the incremental forming process, there have been realised parts using various trajectories for the punch, such as dome, cone frustum, pyramid frustum or straight groove. As part of the tests there have been determined the influence of the geometrical parameters and of the forming manner on the distribution of the strains and on their values, but also on the forces in the process.

The tests for determining the influence of the geometrical parameters on the strains and the relative thinning, but also on the forces on two directions, a vertical one and one in the sheet's plane, were carried out using three types of trajectories: a trajectory describing a straight groove, a trajectory describing a dome and a trajectory describing a pyramid frustum. In order to assess the influence of the geometrical parameters in the case of the trajectory describing a straight groove and of the trajectory describing a dome there have been taken into account as parameters the pitch on vertical direction and the punch diameter, while in the case of the trajectory describing a pyramid frustum there have been taken into account the pitch on vertical direction and the sloping angle of the part's wall.

The tests for determining the influence of the forming manner on the strains and on the relative thinning, but also on the forces on two directions, a vertical one and one in the sheet's plane, were carried out using three types of trajectories: a trajectory describing a dome, a trajectory describing a cone frustum and a trajectory describing a pyramid frustum.

The tests for determining the precision of parts obtained through the incremental forming procedure were carried out on pyramid frustum type parts, the same that were used also for determining the strains and the forces. The parameters taken into account were the same, namely the punch's vertical pitch and the sloping angle of the part's wall.

6 CONCLUSIONS. MAIN CONTRIBUTIONS OF THE THESIS

6.1 Final conclusions

The current doctoral thesis has targeted the studying of the distribution of strains on incrementally formed parts, the determining of forces that intervene in the process and of the geometrical precision of parts obtained by incremental forming.

For the unfolding of the theoretical and experimental researches, two types of materials were used, both having a good formability, the steel DC04 and the aluminium AA6016.

The initiation of theoretical and practical researches and the choice of the research directions and of the employed methods was determined after going through a large amount of speciality documentary materials, presented in the chapter about the state of the art in the domain.

The stages followed during the unfolding of the theoretical and experimental researches had as logistical support the usage of the finite element numerical analysis software package ANSYS LS-DYNA, of the software Matlab for the acquisition and automated processing of experimental data and of the Mathcad software.

A part of the documentation, some theoretical researches and the determining of the metal sheet's mechanical characteristics were carried out during the training stage unfolded by the author at the University of Stuttgart, Germany – Institut für Umformtechnik.

The main conclusions of the researches can be synthetised as follows:

- the single point incremental forming process for metal sheets is a complex, flexible process that is best suited for the production in small batches or for the production of unique parts from the machine manufacturing industry, aeronautics industry, shipbuilding industry, medicine or architecture;
- this process is limited by the large amounts of time required for the realising of parts;
- for the most correct possible modelling of the single point incremental forming process it is necessary to use the finite elements method in the nonlinear domain;

- the main strains, the equivalent strains and the relative thinning have an uneven distribution in the part;
- in the case of dome-shaped parts, the reduction of the punch's diameter leads to a decrease of the minor strains, but the major strains, the equivalent strains and the relative thinning increase, while the increase of the pitch on the vertical direction has as effect a decrease of the values of the major strains and of the relative thinning, but the minor strains increase;
- for the parts of type straight groove, through the decrease of the value of the vertical pitch there are obtained larger minor strains and relative thinning, while through an increase in the punch's diameter the values for all studied characteristics - major strains, equivalent strains, relative thinning - increase;
- for the pyramid frustum type parts, the increase of the vertical pitch and of the value of the part wall's angle lead to an increase of the major strain, of the minor strain, of the equivalent von Mises strain and of the relative thinning;
- in the case of determining the influence of geometrical parameters on the value of forces, on vertical direction and on one of the directions in the sheet's plane, an increase of their value has as effect the increase of the value of forces for all types of parts that were employed during the researches;
- for obtaining a more homogeneous distribution of strains in the part and small values of the main strain and of the relative thinning for dome, pyramid frustum or cone frustum type parts it is recommended to use a spiral type trajectory, for which also smaller values of the forces are obtained, but at the same time it allows the avoidance of sudden variations at the moment when the punch penetrates the material;
- the increase of the part's wall sloping angle leads to a decrease of the value of the level difference between the theoretical profile and the real profile, while an increase in the vertical pitch leads to an increase of these differences;
- although the values obtained for strains and forces through analytical calculation cannot be compared due to using simplifying hypotheses, it can be noticed that the manner in which the increase of the value of the wall sloping angle and of the vertical pitch influence the results is the same, i.e. they lead to an increase of both force components, but also of the strains;

- when assessing the results of the FEM analyses carried out for parts of rectilinear groove type, it was noticed that when increasing the value of the vertical pitch, the minor strains and the relative thinning are smaller, but there are larger major strains, while when increasing the value of the punch diameter the values of all studied characteristics (major strains, minor strains and relative thinning) increase. The differences between the values obtained through FEM and the experimental results are of 2-19 % in the case of the major strain, 1-17 % for the minor strain and 0.5-15 % for the relative thinning;
- in the case of determining the process forces through FEM it can be noticed that the shape of the two curves, of the force component on vertical direction and of the force component on horizontal direction, is the same as the one determined by means of experimental tests. The differences between the values obtained through FEM and the experimental results are of 1.5-20 %;
- for all three parts: cone frustum, pyramid frustum and rectilineat groove, the FEM analyses have shown that the maximal springback is located in the area of the punch's vertical feed.

6.2 Original contributions and possible future research directions

The current doctoral thesis has allowed to bring a series of original contributions to the study of the incremental forming of metal sheets, as follows:

From a theoretical point of view:

- there were synthetised, as a bibliographical study, most scientific results published on a world level that tackle this topic;
- there was elaborated an original classification of the incremental forming procedures for metal sheets;
- in the hypothesis of a plane strain state in the material, there have been determined the mathematical models for determining the strains and forces at the moment of indexing the punch on vertical direction (z), for the case in which a square blankholder plate is used;
- there were realised parametrised models, through the finite element method and with the help of the software packages ANSYS/LS-DYNA for the blank and for

the active elements, for the cases in which there is a circular blankholding plate and a square blankholding plate, respectively;

- there were carried out explicit dynamic analyses for the trajectory describing a straight groove and the strains state was studied;
- there were carried out explicit dynamic analyses for the trajectory describing a straight groove, the trajectory describing a cone frustum and the trajectory describing a pyramid frustum in order to study the forces and the energy consumed in the process, but also the evolution in time of some parameters;
- there were carried out implicit dynamic analyses based on the explicit dynamic analyses, for determining the springback for the three trajectory types.

From an experimental point of view:

- there were carried out tensile tests for steel samples of three thicknesses and for aluminium samples of two thicknesses, in order to determine the mechanical characteristics;
- there were determined the forming limit curves for the materials used during the researches;
- there was realised a virtual data acquisition instrument in the Matlab software;
- there were carried out experimental researches for determining the distribution of the main strains and of the relative thinning, using various trajectories and forming types, and there was analysed the manner in which the geometrical parameters influence their values;
- there were carried out experimental researches for determining the force component on vertical direction and a force component on horizontal direction, using various trajectories and forming types and there was analysed the manner in which the geometrical parameters influence their values;
- there were carried out experimental researches regarding the precision of the parts obtained through this procedure and there was determined the influence of the geometrical parameters on it.

Future research directions:

- experimental determination of the strain distribution on parts with a complex geometry;
- experimental determination of the evolution of the main strains with the help of optical measurement methods, the measurements being done „online”;

- physical realisation of an incremental forming machine;
- determining the strain distribution on the part also for other types of materials: materials that are difficult to form, materials that are easier to form in semi-hot conditions, welded materials, PVC, sandwich materials, laminated materials etc;
- determining the methods for obtaining Forming Limit Diagrams for various combinations of materials and thicknesses.

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