KAUNAS UNIVERSITY OF TECHNOLOGY

MECHANICAL ENGINEERING AND DESIGN FACULTY

Audrius Venckevičius

REASEARCH OF INCREMENTAL SHEET METAL FORMING WITH ADDITIONAL SUPPORT

Master's Degree Final Project

Supervisor

Assoc. prof. dr. Marius Rimašauskas

KAUNAS, 2016

KAUNO TECHNOLOGIJOS UNIVERSITETAS

MECHANIKOS INŽINERIJOS IR DIZAINO FAKULTETAS

Audrius Venckevičius

METALO LAKŠTO FORMAVIMO SU PAGALBINE ATRAMA TYRIMAS

Magistro Baigiamasis Darbas

Vadovas

Doc. dr. Marius Rimašauskas

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KAUNAS UNIVERSITY OF TECHNOLOGY

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"Research of incremental sheet metal forming with additional support"

DECLARATION OF ACADEMIC INTEGRITY

____ June 2016

Kaunas

I confirm that the final project of mine, **Audrius Venckevičius**, on the subject "Research of incremental sheet metal forming with additional support" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

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Approved:	____________________
Head of	*(Signature, date)*
Production engineering	
Department	***Kazimieras Juzėnas***
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MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Research of incremental sheet metal forming with additional support.

Approved by the Dean Order No.V25-11-7, 3 May 2016

2. Aim of the project

To analyze incremental sheet metal forming technology with additional support.

3. Structure of the project

Research part: sheet metal forming for production of prototypes; forming techniques principles; working parameters importance in forming process; equipment utilized in production process. **Project part:** acquisition of material for production testing; sheet metal forming using forming tool; additional support application; investigation of result. **Economic part:** determination of cost for production. **Graphic part:** Schemes, figures, graphs, tables, drawings.

4. Requirements and conditions

Material in relevant topics is analysed and concluded. Tests are done using scientific methods, have clear objectives, performed in a logical order, relevant results or conclusions. Suggestions for improvements has to be reasoned and supported by an implementation plan. Economic analysis has to refer to relevant statistics or calculations. Graphic part has to be understandable, logically presented.

5. This task assignment is an integral part of the final projec

6. Project submission deadline: 2016 ________ __st.

Given to the student

____

Task Assignment received ____________________ ____________________
(Name, Surname of the Student) *(Signature, date)*

Supervisor ____________________ ____________________
(Name, Surname of the Student) *(Signature, date)*

Venckevičius Audrius. Research of incremental sheet metal forming with additional support. Master's thesis / supervisor assoc. prof. dr. Marius Rimašauskas. The Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study area and field: Production and Manufacturing Engineering, Technological Sciences.

Keywords: Incremental sheet metal forming with additional support, forming angle, coordinate measuring machine

Kaunas, 2016. 52 p.

SUMMARY

Nowadays the market is in an increasing demand of agile manufacturing technologies that can be easily applied to the market changes and provides ability to maintain competitiveness of a company. Incremental sheet metal forming with additional support can be applied for small-batch and prototype production, because this process does not require high investment and can be easily applied. In the first chapter important parameters of incremental sheet metal forming are analysed. Moreover, similar forming technologies are overviewed.

In the second chapter of the paper work technology of incremental sheet metal forming with additional support is analysed. The process is carried out utilizing CNC milling machine, forming tool with spherical tip, sheet metal fixture and wood support.

The third chapter presents results after the process. Experiments were carried out using two techniques: with support and with no support. Forming angle and surface deformation was measured using coordinate measuring machine (CMM). Results and comparisons of both techniques are presented.

Venckevičius Audrius. Metalo lakšto formavimo su pagalbine atrama tyrimas. Magistro baigiamasis projektas / vadovas doc. dr. Marius Rimašauskas. Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

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SANTRAUKA

Šiais laikais rinkoje vyrauja vis didėjanti paslankių gamybos metodų paklausa, kuri leistų greitai prisitaikyti prie rinkos pokyčių ir suteiktų galimybę išlikti konkurencingais. Palaipsnis metalo lakšto formavimas su pagalbine atrama gali būti naudojamas mažaserijinei arba prototipų gamybai, nes šis procesas nereikalauja didelių investicijų, yra lengvai pritaikomas ir efektyvus. Pirmajame skyriuje yra apžvelgiami palaipsnio metalo lakšto formavimo parametrai. Plačiau aprašomos panašios metalo lakšto formavimo technologijos.

Antrajame skyriuje nagrinėjama palaipsnio metalo lakšto formavimo su pagalbine atrama technologija. Bandymai atliekami naudojant CNC frezavimo stakles, formavimo įrankį su sferine galvute, metalo lakšto fiksavimo rėmą ir medinę atramą.

Tiriamojoje dalyje atlikti bandymai nustatant formavimo kampus bei paviršiaus deformacijas. Bandymai atlikti dviem būdais: su pagalbine atrama ir be atramos. Formavimo kampas ir įvykusi deformacija nustatyti naudojant koordinatę matavimo mašiną. Pateikti abiejų formavimo būdų rezultatai ir palyginimai.

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INTRODUCTION

Incremental sheet metal forming is well known manufacturing process in automotive, aerospace and other industries where exists necessity of good quality complex parts and prototypes that can be produced using nowadays technology. Due to increasing demand and competitiveness conventional manufacturing technologies are desired when production is of a small-batch quantity. Manufacturing technologies have to be flexible and apply new manufacturing solutions to fulfil market demand.

The work studied deformation and forming angle of aluminium AW1050DDQ. Two techniques for production were used: with support and with no support. The study also includes measuring of parts geometry with conventional CMM machine. This paper work provides knowledge for better understanding how geometrical accuracy can be enhanced.

Data analysis and comparison of both techniques is presented in the last chapter of the paper work.

The main aim of the work is to analyze incremental sheet metal forming technology with additional support.

Main tasks:

1. To analyze incremental sheet metal forming technology and determine parameters affecting quality of the prototype.
2. To develop equipment for sheet metal forming with additional support.
3. To produce 6 prototypes with and with no support in order to examine quality and formability.
4. Determine prototypes forming angle and forming depth in order to compare with nominal values.

1. LITERATURE OVERVIEW

1.1 Introduction to Sheet Metal Forming Process

Appearance and application of Incremental Sheet Metal Forming process has been enhanced and driven by intensive competition in manufacturing sector. Customer requirements are the main task to be fulfilled by companies, pushing forward to not only for high quality products, but also new efficient and flexible technologies for production. Furthermore, there is increasing demand in the market for small batch production, prototypes and customization. ISMF as a technology provides more flexibility capabilities and relatively lower operating costs comparing with other, traditional, technologies, e.g. deep drawing and stamping. These technologies require high investment and expenditures, low flexibility, which is crucial for flexible manufacturing. ISMF technology does not require dies (die-less forming) for production and is highly flexible for prototyping, manufacturing of single-piece or small batch components. Sheet metal forming for utilizing this method requires of a conventional multi-axis CNC milling machine and can be done with relatively simple tools, usually hemispherical tip tool which is shown in Figure 1.

Nevertheless, main difference comparing similar techniques, for example, shear forming and spinning, is the ability to move in all axes. This enables to move tool in such a manner providing possibility to produce symmetrical and asymmetrical shapes. Die-less and simple forming rig are important advantages leading to flexibility. Cycle time, surface quality and cost depend on many factors that are not clear enough to be constant. Many researches were done in order to make this technology parameters constant. Tool path optimization is significantly important and has big impact on quality.

For application of ISMF process simple and basic setup consists of main components that are shown in Figure 2, where all components are noted. The rig itself is on the worktable of multi-axis CNC milling centre and serves as a main platform for forming. The blank-holder restricts possible movements of the blank material when forming tool touches forming region. Stability ensures more concentrated force applied to the material and high accuracy can be achieved.

Figure 1.1. Forming tools for SPIF [2]

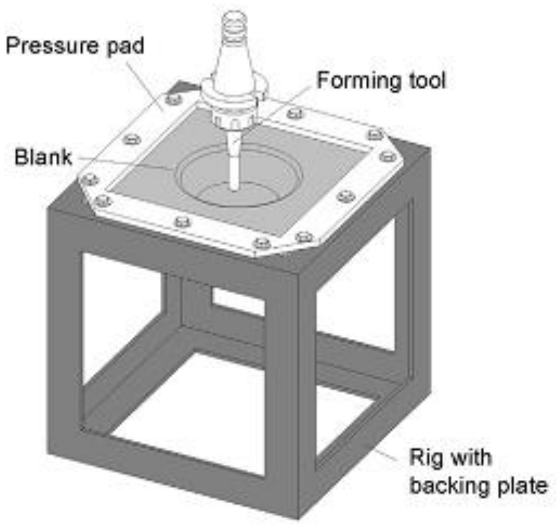


Figure 1.2. Schematic representation of SPIF setup [2]

Common ISMF parameters and parts are shown in Figure 3. It represents simple configuration for forming cone, listing components that are encorporated in operation. The initial sheet thickness is noted as t_i, the final thickness of sheet as t_f. Values mentioned previously are in millimetres. Forming angle of a semi-cone is designated as β and measured in degrees.

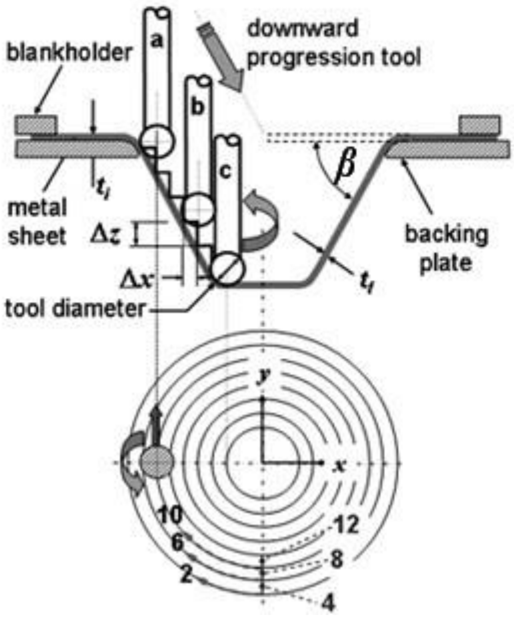


Figure 1.3. ISMF of a semi-cone [3]

Axial depth Δz is known as incremental stepover size. It describes the amount of blank material deformed in each tool pass. Stepover size has significant effect on surface quality and time consumption. These parameters are managed by CAM software. Another parameter controlled by CAM and CNC milling machine is spindle speed. Rotating tool generates heat when in contact with sheet metal at a certain spot due to friction. In this case heat can be reduced by changing machining parameters or applying lubrication.

The angle between horizontal sheet clamped with blank-holder and deformed surface of the blank is defined as forming angle *β.* The forming angle can be used as a measure of material formability. The maximum angle (*β max*) is the greatest angle formed shape without any failures [4].

1.1.1 Tool path generation

Tool path generation for the process has direct impact on the dimensional accuracy, surface finish, formability, thickness variation and processing time. It is determined that parts produced by applying spiral tool path obtained higher level of accuracy when comparing with results of the process when contour tool path was utilized. For finishing of required dimensions for part contour milling tool path is used. Usually movement of the tool is defined by vertical stepdown Δz.

Size of stepdown Δz usually is fixed for each layer contour of the part. Moreover, contour milling technique is used for the most part for generation of tool trajectories. Main disadvantage of this technology is that it leaves visible marks of the path on processed surface and enhances surface waviness leading to lower quality of the part. Surface quality depends on theses parameters: forming tool radius; size of vertical stepdown Δz and drawing angle, spindle rotation speed and applied lubrication [5].

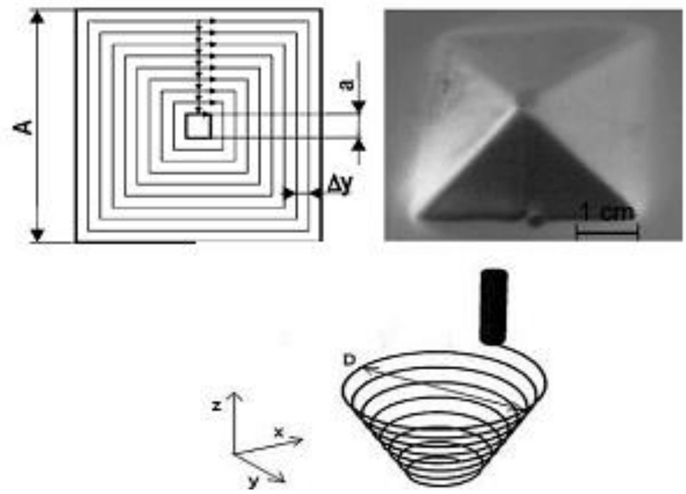


Figure 1.4. Tool trajectories [1]

The main difference between contour milling and spiral tool path is that spiral tool path produces continuous tool motion along required contour of the prototype part. Main advantage of this technique is that no tool traces are left after processing. For multistage forming process multiple tool path technologies can be applied by adding transitional contours that are described within the recess of parts final surface. This strategy typically is characterized by limited drawing angles and bends. This is similar to milling operation when roughing step is done. Furthermore, it is repeated by finishing pass. Here both tool path techniques can be used in order to perform required shapes by incremental sheet metal forming process without any errors aiming to meet necessary level of quality.

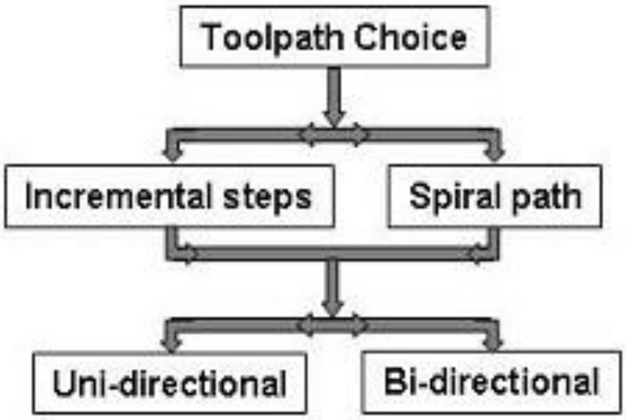


Figure 1.5. Suitable toolpaths for ISMF

There exists few options for CNC milling center to control path of the forming tool (Figure 1.5). Features typically depend on chosen software. In most cases using different CAM software for forming operations can be very problematic, because usually it is applied for milling operation. In order to proceed operation with no failures it is necessary to test generated CAD file. If there are no potential errors the process can be continued. MASTERCAM software can be utilized for checking of errors. It is known that CAM software is not created for increment forming process, it is highly recommended to simulate tool path for the process. CAM software can be applied for incremental sheet metal forming operation by using the finishing pass commands as in milling process and this allows to generate decent CNC program with chosen forming tool.

1.1.2 Sheet material

Formability is one of the major factors in SPIF operation field. It depends on used material mechanical properties, such as, hardening coefficient, anisotropy, ultimate tensile strength and percentage elongation. Fratini was aiming to establish these properties in experimental way [7]. Most common materials was chosen for the experiment from automotive and other industries utilizing sheet forming. Results of experiment were investigated and allowed to carry out most important mechanical characteristics. Highest hardening coefficient and highest percentage of elongation can be concluded as highest material formability in SPIF.

1.1.3 Forming angle

This angle can be founded between horizontal plane of the sheet and inclined (formed) surface. It is known as forming angle *β*. Magnitude of this angle is measured in degrees and represents the ability to be applied for SPIF. The higher value of angle results in greater formability. This peculiarity mainly depends on nature of sheet material. Angle β_{max} is the highest achieved result of operation before failure occurred. During experiments predictions were made to predict maximum forming angle evaluating material properties and forming operation parameters according Equation which is shown below [8]:

$$\beta = \frac{\pi}{2} - e^{\varepsilon t} \quad (1.1)$$

Here:

t – fracture thickness at the limit of formability;

εt – thickness strain.

The equation represents the onset of fracture because it combines the ideas of both fracture forming limit in principle strain space and the maximum forming angle at the onset fracture [8].

1.1.4 Tool size

In order to choose forming tool correctly it is necessary to know requirements for surface finish since it is clear that surface quality and formability parameters are dependent on size of the tool. Usually tool size is characterized with tip radius or tip diameter. Selection of large size tool would lead to minimization of processing time, but other parameters as vertical stepdown is of high importance. The main benefit of tool with large radius is reduction of tool working trajectory marks as the groove made after full pass is less visible. Furthermore, higher tool tip radius provides a larger area of deformation. Moreover, an increased forming tool size allows increasing size of the vertical stepdown Δz [9]. The size of tool also can have influence on the process with vertical stepdown. Smaller size of tool diameter and lower value of Δz leads to lower possibility of failure during the process.

1.1.5 Tool speed

Forming speed is divided into two main values: rotation speed (RPM) and feed rate. First values describe the speed of CNC milling machine spindle which rotates along its axis. Second value feed rate describes the tool speed when it is moving along axis of the trajectory. The exact effect of spindle rotation is still unclear. During experiments it was concluded that generated heat between tool and sheet due to friction enhances formability. Poor lubrication and too high heat concentration can also have negative effects, i. e. decreased surface quality, higher coarsity, tool wear, forming traces. Furthermore, waviness is another property which can occur due to wrong operational regimes.

1.1.6 Vertical stepdown Δz

The vertical step down (Δz) between consecutive layers of forming paths has a significant effect on the process. In the case of helical trajectories, the step down is the vertical distance between paths at consecutive laps.

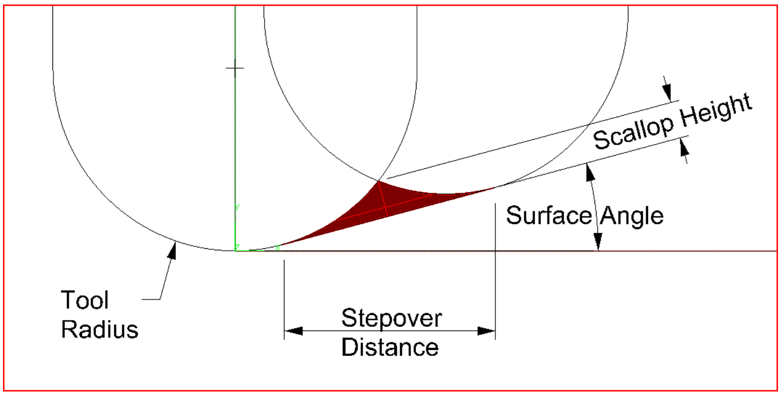


Figure 1.6. Stepover distance [14]

When the forming tool travels along chosen trajectory, tip of the tool leaves groove shaped trace on the deformed surface. Size of the groove mostly depends on tool radius. In most cases a smooth surface finish is required, so tool trajectories must overlap in order cover single traces after each pass is performed. For parts with constant angle of the wall selection of vertical stepdown is easier and typically depends on provided requirements for surface roughness of part. More difficulties occur when the angle of sidewall of desired shape increases along its contour. For a constant vertical step down, the horizontal distance between forming trajectories alternates with the wall angle of the geometry as presented in Figure 1.7 [9].

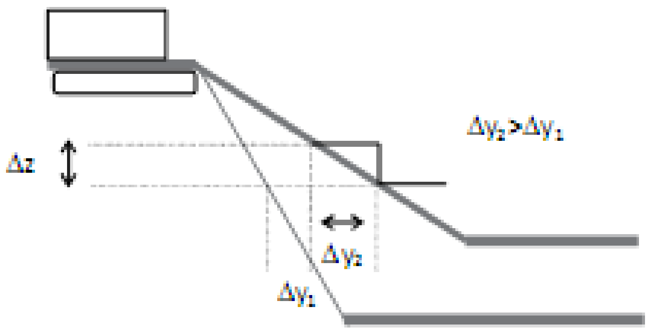


Figure 1.7. Effect of the forming angle on the distance between trajectories [9]

Higher level of deformation can be done due to altered vertical stepdown at each movement of tool. The increasing step down has main disadvantage affecting formability of chosen material and leading to higher chance of failure [11]. Increased value of operating forces when tool is in contact with parts surface can have unfavourable effects and this leads to damage and geometrical inaccuracies. Since there is no know-how for the choice of vertical stepdown Δz size it is usually based on workers experience and optimal values for the process is obtained in experimental manner.

1.1.7 Lubrication

Lubrication is one additional factor that must be taken into account. Lubricant can play important role in quality, waviness and surface roughness of the part. Moreover, it must be conducted and Bramley [12] made a set of tests to determine how much lubrication changes the surface roughness. The upshot of the tests was the type of lubricant did not appear to be a factor, but lubrication is necessary to obtain a smooth surface. Table 1 shows results obtained results of tests.

Table 2.1. The effect of speed and lubrication on surface roughness [13]

Shape	Lubrication	Spindle speed, RPM	Roughness, R_a	Roughness, R_t
Sphere	None	1000	9.42	74.73
Pyramid	Grease	1000	1.24	14.43
Sphere	Oil	20	0.538	5.09
Pyramid	Grease	20	0.564	5.43

From this table it can be stated that application of lubricant in SPIF operation can increase surface quality significantly.

1.2 Multistage forming

Multistage forming is usually adopted to form those parts which have steep angles or even vertical walls during incremental sheet forming process. All necessary parameters for operation are chosen in accordance to material thickness. Maximum forming angle can be founded experimentally when performing operation until failure. For a single-stage incremental forming, the sheet thickness will generally conform to the sine law [15]:

$$T_f = T_0 sin \propto \quad (1.2)$$

Here:

T_f - final thickness of the finished part;

T_0 – initial thickness;

α – is angle of inclined surface.

Obviously, if α is rather small or even equals to 0°, the ultimate thickness will be impossible to meet the requirement by using single-pass forming method. In this case, a multistage incremental forming is needed. Unlike a single-pass forming whose tool path is directly generated from α, a multistage process will achieve the final part through some intermediate shapes. Each intermediate shape represents a forming stage which is basically identical to a single-pass incremental forming. For simplicity, take a double-pass forming (n=2) [9]. Utilizing multistage process better geometrical accuracy can be achieved and resulting to successive forming operations. Furthermore, multiple steps can increase stiffness and local spring-back reduction.

1.2.1 Incremental sheet metal forming with additional support

Incremental sheet forming is successfully applied in various industries where complexity and customization is major factor for decision to develop this technique. However, spring-back phenomenon has still been a leading forming defect of incremental forming and severely limits the further application of this technology. As spring-back happens during the whole forming process and is influenced by numerous factors, it is hard to seek an effective way to deal with this problem [20]. To achieve higher geometrical accuracy additional supports are introduced in the process. Usually, adopted supports were rigid and this leads to extra expenditures and possible delays in manufacturing. Elastic supports have considerable elasticity comparing with rigid supports. Research was done by Juchiao Li and three materials were investigated:

- Wood;
- Rubber;
- Polyurethane.

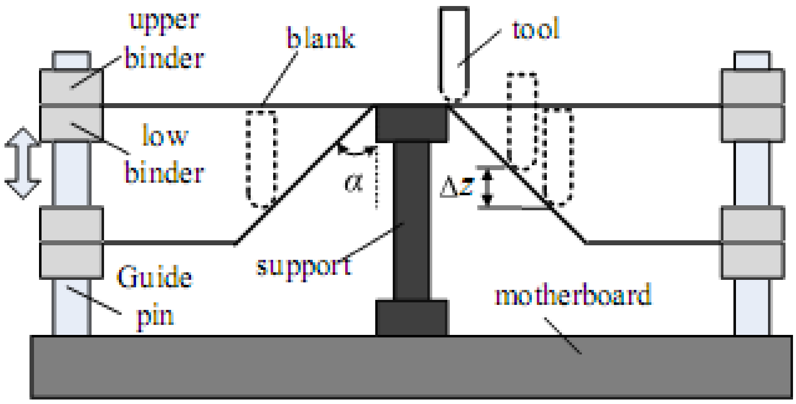


Figure 1.8. Setup of incremental sheet forming [20]

The essential difference between the three materials is that polyurethane material has the maximum elasticity, rubber material - less, and wood material - least [20].

Results of the investigation have shown that greatest geometrical accuracy and surface quality was achieved by using wooden support.

1.2.2 Advantages and disadvantages of the ISMF process

The main advantages of the ISMF process [16]:

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

The main disadvantages of the ISMF process [17]:

- SPIF process takes longer forming time comparing with conventional deep drawing processes;
- SPIF less geometrical accuracy especially at bending edges area and convex radius;
- Process suitable only for small batch production;
- To achieve vertical angle multistage strategies must be used;
- Spring-back occurs even though it can be minimized by correction algorithms.

1.2.3 Incremental sheet metal forming operation

Incremental sheet forming process is appealing for its flexibility and variety of use for small lot production or prototyping. Since it is not suitable for mass production, general part of production is complex and/or with special requirements. ISF is applicable in aviation, automobile, medical and other industries. Examples of applications of ISF are shown below:

- Production of heat or vibration shield (Figure 1.9);
- Reflective surface of headlights (Figure 1.10);
- Solar oven (Figure 1.11);

- Silencer housing for trucks (Figure 1.12).

Figure 1.9. Heat or vibration shield [18]

Figure 1.10. Reflective surface of the headlight [18]

Figure 1.11. Solar oven [18]

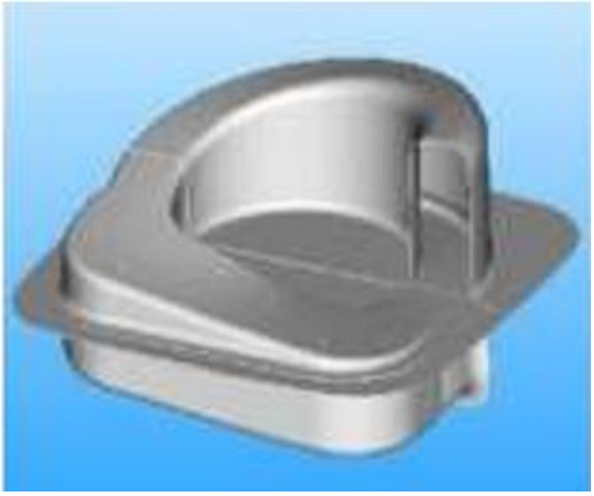


Figure 1.12. Silencer for truck [18]

Medical application for producing prosthesis for human. This technology for medical use will be desirable due to satisfactory accuracy and low surface roughness.

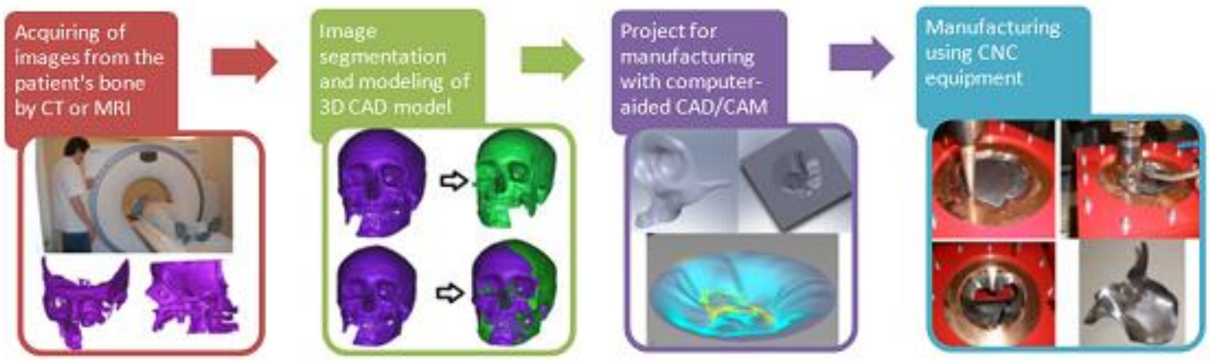


Figure 1.13. Production cycle of implant [19]

All these products are manufacture utilizing ISF technology. Nevertheless, this technology can be used for aerospace, train, boats and many other applications.

1.3 Incremental sheet metal forming with counter tool

The Incremental Forming with Counter Tool is also known as Kinematic Incremental Forming is a technology that doesn‘t require any backing plate, but there will be counter tool which moves along the same trajectory as main forming tool by supporting each other instead [18].

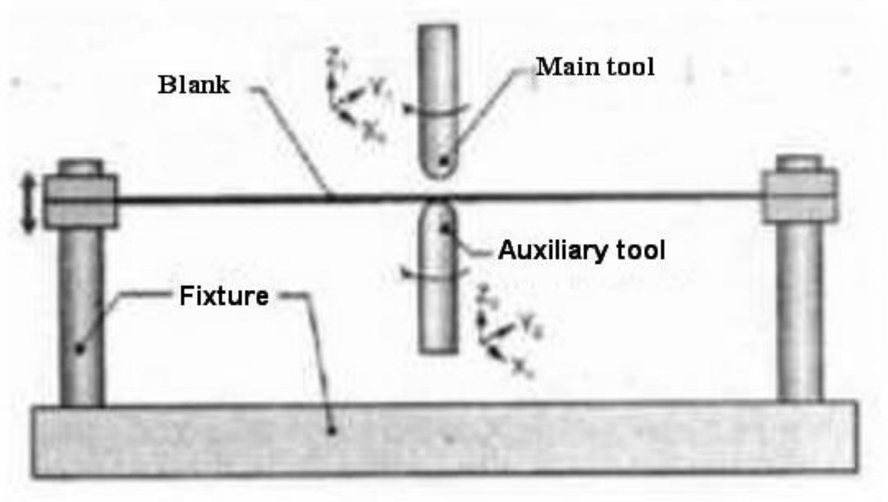


Figure 1.14. IFWCT schematic representation [18]

1.4 Two point incremental sheet forming

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

1.4.1 Two Point Incremental Forming with partial die

In this process, sheet is clamped without able to move up and down due to supported post under some essential area of the blank. Tool moves as incremental forming movement follow support tool which stay fixed below sheet, however part is formed from the inner area of blank to the outer side. There is no wrinkling in this process due to local shear occurs rather than stretching and the rest of sheet will maintain its original dimension regarding to Jeswiet [3]. This process requires static support which allows improving accuracy of part geometry. Advantage of this process is that support post can be adapted for production of other similar geometry parts (Figure 1.15).

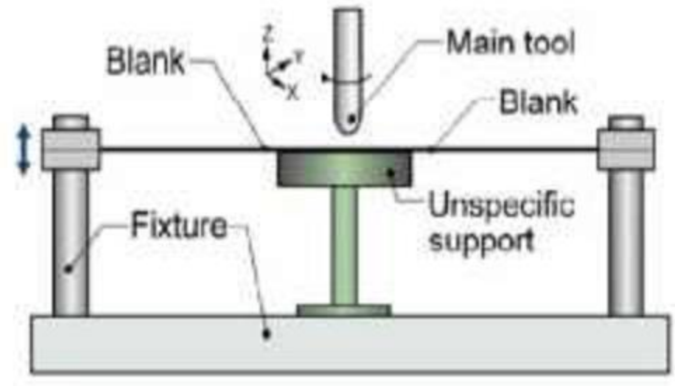


Figure 1.15. Schematic representation of TPIF with partial die [3]

1.4.2 Two Point Incremental Forming with full die

TPIF technique with full die is not considered as a die less approach. Main advantage is relatively higher accuracy of geometry, because the blank material is constrained by the forming tool and dies during operation to reduce possible movements as much as possible (Figure 1.16). Time consumption increases and for new part new die is needed.

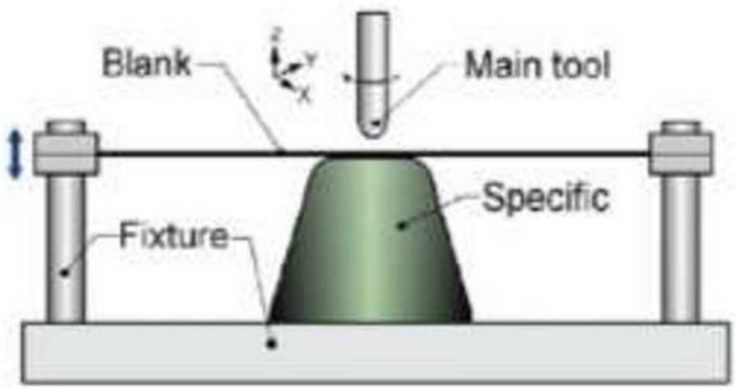


Figure 1.16. Schematic representation of TPIF with full die [3]

1.5 Spinning forming

Spinning forming process is the metal forming process by which sheet metal is rotated at high speed and formed into axially symmetric part. Part can be formed by hand (low accuracy) or by CNC machine (high accuracy) by applying localized force to a work piece when it is spinning. There are two main types of spinning forming process: Convention and Shear spinning.

Conventional Spinning (Figure 1.17) is steadily formed by using roller or rounded tool. Tool pushed against the blank until roller conforms to the contour mandrel. Final part is definitely having smaller diameter than initial blank but has constant thickness. This process is suitable for small series of production due to many sequences of steps hence low tool production cost in this process is a great choice [3].

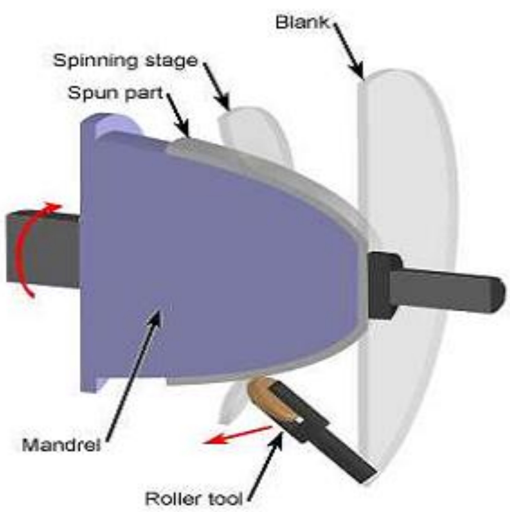


Figure 1.17. Conventional spinning [3]

In Shear spinning (Figure 18), roller will have two actions of bending sheet against mandrel and also applying downward force while rotating. Regarding to that action causing outer diameter of final part equal to initial part but wall thickness will not be constant.

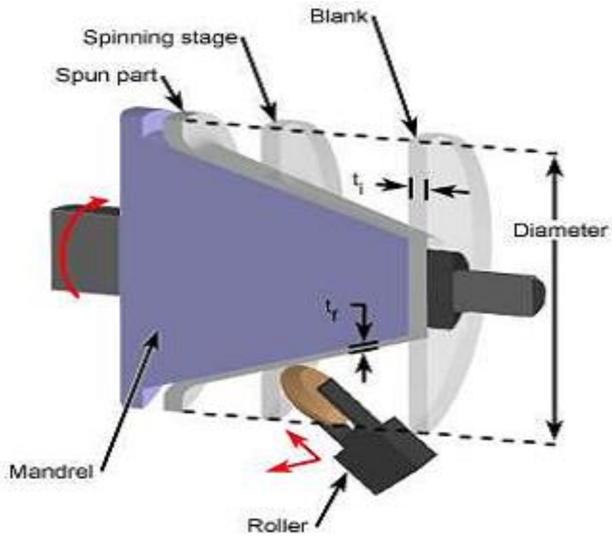


Figure 1.18. Shear spinning [3]

1.6 Laser forming process

Laser forming is a conventional non-contact method, providing forming of both, metallic and non-metallic products. It is formed by introducing thermal stress into the surface of work piece area by irradiation laser beam which thermal stress induce plastic strain bending the material and result in local elastic plastic buckling [3]. Disadvantage of this method is high energy consumptions, high cost, skilled worker, material preparation.

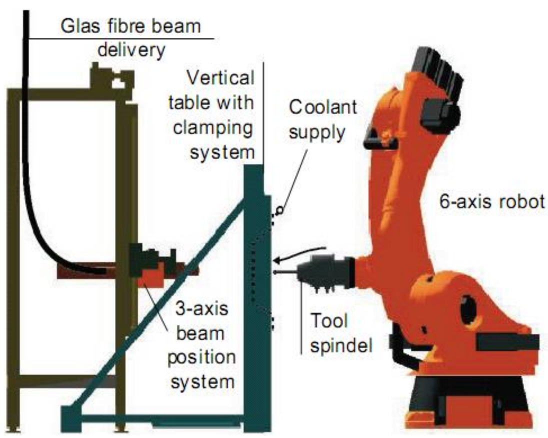


Figure 1.19. Laser forming process scheme [3]

1.7 Water jet forming

Water Jet Forming is one of sheet forming process that no rigid tool required. It was developed specially for a small batch of manufacturing of non-symmetrical shape of shallows shell. This method can erasure the tool marks and form without lubricant oil. To use water jet forming method, membrane theory and momentum theory of hydrodynamics must be considered [21]. Main advantages of Water Jet Forming is flexibility, low number of tools needed, low cost, good surface quality since no rigid tool is interacting with surface.

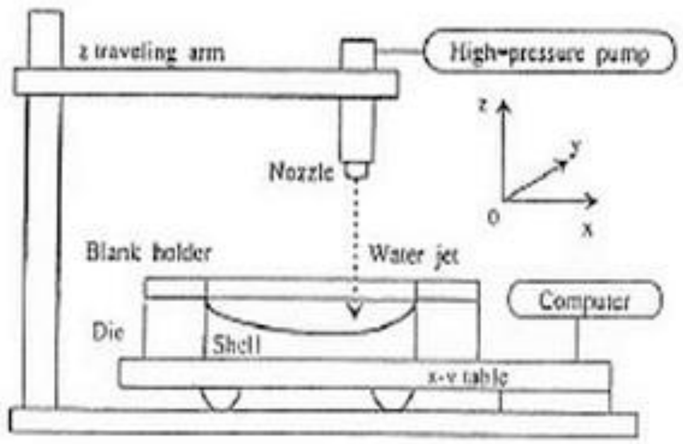


Figure 1.20. Schematic diagram of water jet forming [21]

1.8 Deep drawing process

Deep drawing process is one of many other sheet metal forming process technologies. This technology is well known and is widely applied in different industries, e.g. automotive, aerospace, food industries. Deep drawing provides ability to produce high accuracy and complexity shapes for large batch production.

For deep drawing operation die set is required. Typically die is produced for only one type of part, so flexibility is very low comparing with ISMF. Sheet material is placed on die, which is processed identically as the part to be formed. The blank holder restricts any possible movement of the blank material by holding it at places where no deformation is done. Nevertheless, the main purpose of the blank holder is to prevent wrinkling and unnecessary deformation of the sheet, also sliding of the blank during the drawing process is reduced significantly. After preparation for the drawing process, the punch is moved downwards. Local deformation is applied and sheet material obtains required shape [22].

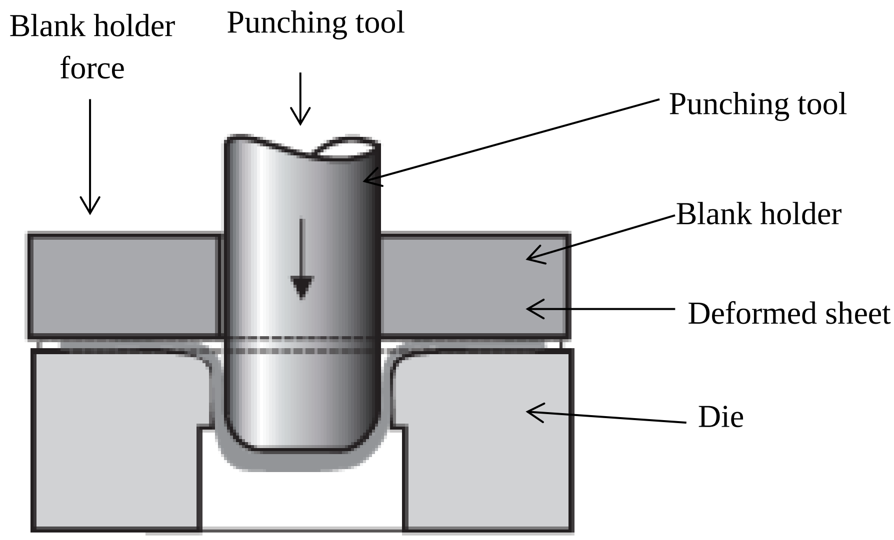


Figure 1.21. Deep drawing process illustration [20]

Deep drawing is also widely applied in food industry for production of cans, containers and other necessary equipment. Other wide fields of application are automotive and aerospace industries. Here deep drawing technology is performed using flat sheet material. Size of the blank depends on size of the part to be produced. Most common material for deep drawing process is aluminium alloy or steel. Typically this type of sheet material is prepared in rolling operations. During rolling operation roughness is applied for the material. Since the wear occurs lubrication is introduced in the process. The main objective is to reduce friction and wear between tool and the work-piece in order to prevent occurrence of small scratches on the blank material that is used for further production [22].

1.8.1 Contact regions of deep drawing

In deep drawing process when two separate bodies are in contact and movement against each other occurs, friction appears. Origin of friction in this process can be traced from contact region between forming tool and the blank material. In deep drawing number of contact and friction regions can be founded and these regions are presented in Figure 1.22. Region 1 and Region 2 are considered as contact regions between the blank fixture and sheet metal, and die set and sheet material respectively.

In above mentioned region drawing occurs between the blank holder and die and deformation of the sheet is relatively not high. Region 3 illustrates contact that occurs between rounding of the die and blank.

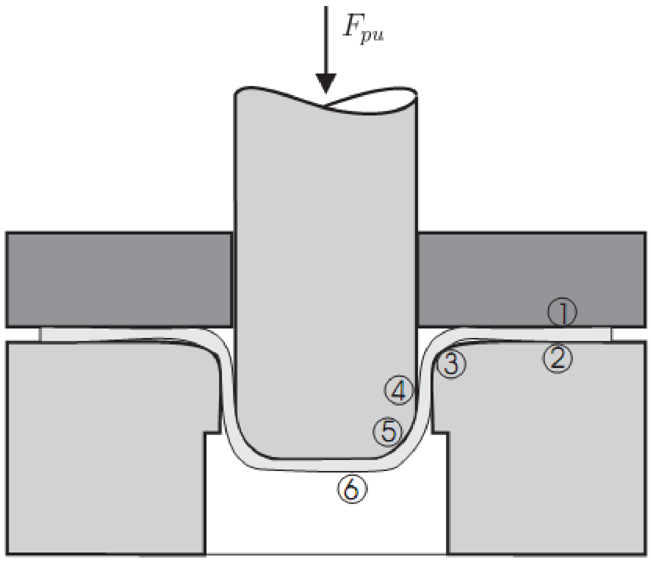


Figure 1.22. The contact regions in deep drawing forming process [22]

In Region 3 the sheet material is bent and unbent. Values of nominal pressure in this region can be of 100 MPa. In Region 4 contact between the punch and blank material occurs. Here the sheet is deformed along direction of the punch, but no physical contact occurs. Contact of the punch radius and blank takes place in Region 5 and the deformation of the material in this region is increased. Last contact region where contact between end of the punch and blank appears is Region 6. It is known that friction in this region is much lower and this region does not affect drawing process. In order to perform deep drawing process successfully it is needed to maintain high friction in Region 5 to assure that blank is formed as required according to movement of punch. Low friction values must be ensured in Region 1, 2, 3 in order to prevent failures during operation [22].

2. ANALYSIS OF ISMF TECHNOLOGY AND EQUIPMENT

In this chapter CNC machine, forming tool, forming path, rack and support will be analyzed in order to produce truncated cone shape out of sheet metal utilizing Incremental Sheet Metal Forming operation.

2.1 CNC machine

In order to perform forming operation from sheet metal to chosen shape, it will need to utilize CNC machine. All the experiments were carried out at the Kaunas University of Technology, Faculty of Mechanical Engineering and Design. To perform ISMF process Deckel Maho DMU 35M CNC universal machining centre was utilized and is shown in Figure 2.1:

Figure 2.1. Universal machining center Deckel Maho DMU 35M

Table 2.1. Technical data of machine center [23]

Work room		
X-axis	mm	350
Y-axis	mm	240
Z-axis	mm	340
Main drive		
Speed range	rpm	20-6300
Torque	Nm	80
Power (40/100% ED)	kW	10/6.3
Axis drive		
Feed	mm/min	5000
Fast traverse	m/min	5
Tool holding		ISO 40
Control		
Sinumerik 810 D with Shop Mill user interface		

The machine's stability and precision plus the fact that it can process 5 sides in a single clamping makes the DMU 35 M the ideal machine for modern training purposes, use in workshops, maintenance, tool-making and the construction of jigs and fixtures.

2.2 Forming tool

The forming tool is made from Steel 45. Heat treatment was applied in order to increase hardness and improve wear resistance of the tool. For the process of ordinary elements tool end is shaped as a sphere. In current experiments used tool diameter was 10 mm in order to form sheet metal of 1.5 mm thickness (Figure 2.2). Tool properties can also influence and show formability of the blank material, surface finish and point of fracture in case of an error.

Figure 2.2. Forming tool with 10 mm sphere diameter

2.3 ISMF clamping system

In order to perform ISMF operation with CNC universal machining center, clamping system was utilized. 3D model of the clamping system was made and shown in Figure 2.3.

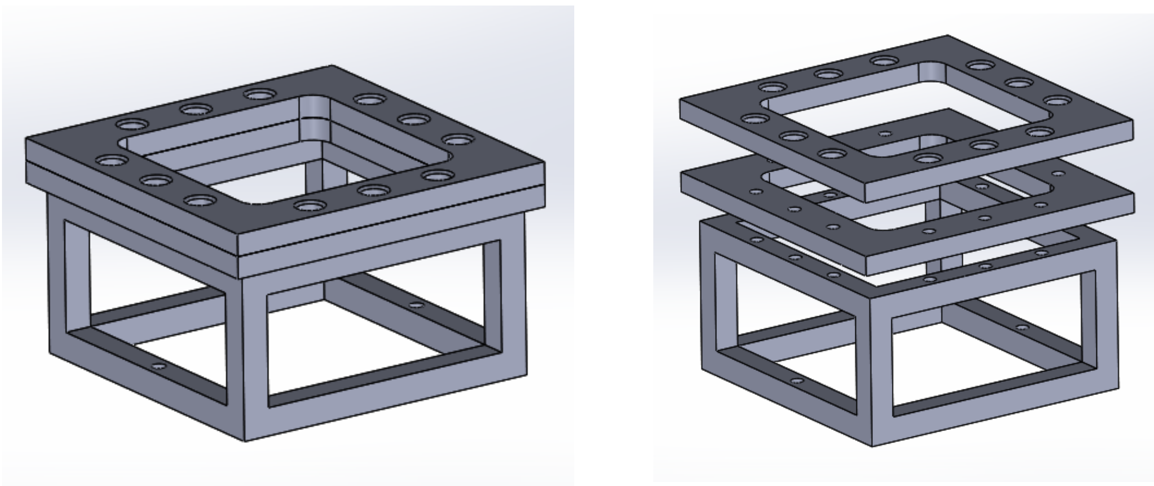


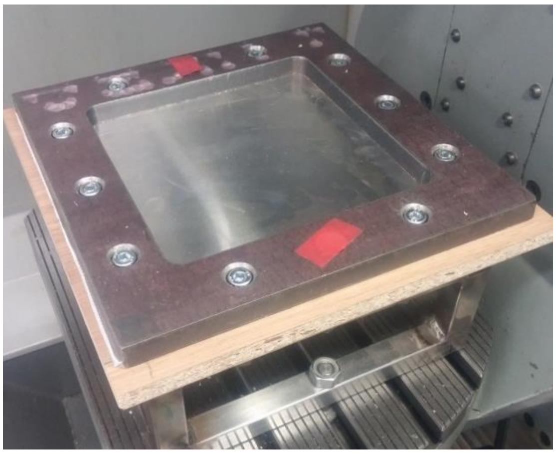
Figure 2.3. 3D model of the clamping system

Clamping system consists of the rigid frame (a), which is fixed on the working table of the CNC machine, the blank holding plate (b), with fixed wooden support (c) and with sheet metal (d). All the parts of the clamping system are shown below (Figure 2.4):

a) Rigid frame

b) Blank holder plates

c) Assembly with support



d) Assembly with support and sheet metal

Figure 2.4. Clamping system

Complete assembly of the clamping system with support and sheet metal is fixed to the working table of CNC milling machine by two screws through the holes that were made in the frame. Rigid fixture of the frame enables to perform deformation process by interaction of the tool to the sheet metal surface and restricts movement of the blank material or frame itself in any direction leading to better accuracy of the final result. Working zone for the forming tool was specified with indicator tool, fixed in the spindle of the machine, before the experiment. Surface area that can be processed is 170 mm by 170 mm.

2.4 Material and lubrication

For this experiment aluminium EN AW150DDQ material was chosen. Aluminium of this grade is of common usage due to its properties where relatively high moderate strenghtness is required. Furthermore, EN AW150DDQ material is known for high corrosion resistance, high ductility and highly reflective surface finish.

Applications of the material:

- Chemical and food industry processing equipment;
- Insulation, vessels, piping;
- Packaging: containers, foils, collapsible tubes, radiator tubes;
- Architectural panels.

Thickness of the selected material was 1.5 mm. The sheets were cut in pieces of 250 x 250 mm as shown in the Figure 2.5.

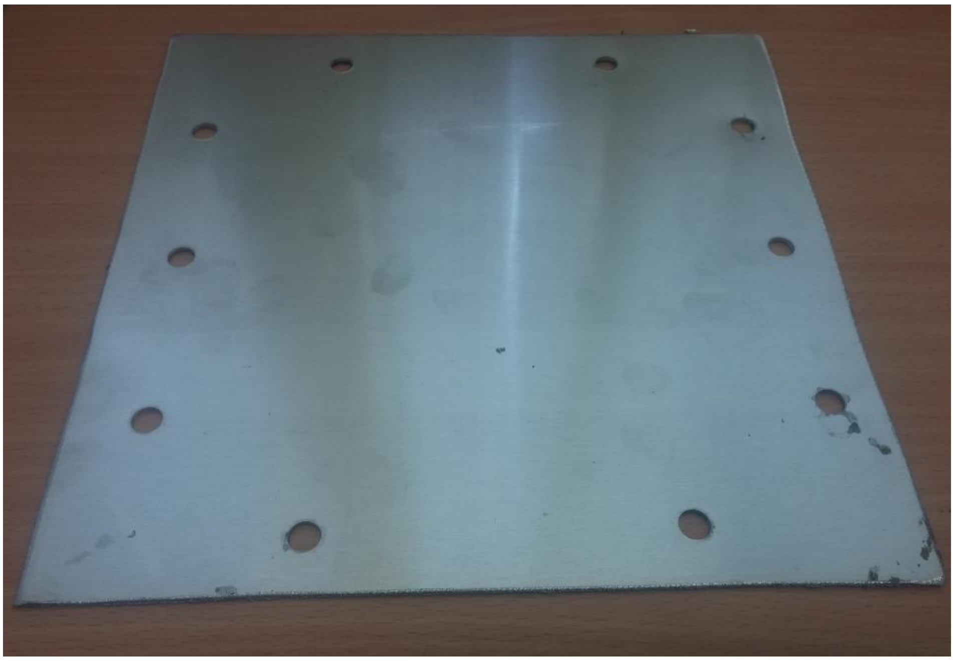


Figure 2.5. Aluminium blank example

After preparation of the material, it must be sustained undamaged at any place of the surface, keeping in mind the fact that this grade of aluminium can be deformed easily and affect quality properties of the product. 10 slots of 10 mm diameter were made on the sheet to make places for screws in order to connect the fixing plates successfully.

Aluminium alloy AW1050DDQ is composed of many different materials according to Table 2.2.

Table 2.2. Chemical composition of AW1050DDQ [24]

	Si, %	**Fe, %**	**Cu, %**	**Mn, %**	**Cr, %**	**Zn, %**	**Ti, %**	**Al, %**	**Others, %**
AW1050DDQ	0.25	0.40	0.05	0.01	0.01	0.07	0.05	99.50	0.03

From Table 2.2 that is provided above it is clearly seen that this type of aluminium has low impurities and 99.5% of aluminium and in most cases can be considered as pure aluminium.

Table 2.3. Mechanical characteristics of AW1050DDQ [24]

Specification	**Symbol**	**Units**	**Value**
Tensile strength	Rm	N/mm^2	100-135
Yield strength	f_y	N/mm^2	Min 75
Shear strength	G	N/mm^2	70
Elongation	A	% (A50)	4-8
Brinell Hardness	-	HB	35
Elastic modulus	E	MPa	69000

Lubrication is important for this process. Application of lubricant is necessary for smooth forming tools movement along the surface of the sheet in order to reduce roughness of the final surface, reduce wear of the tool due to friction between contacting surfaces and to reduce heat generated from tool tip friction when traveling along generated path. Exact amount of lubricant necessary for the process is unknown and is added on the surface approximately.

2.5 Tool path

In order to process CAD model of the required part, it is necessary to generate the pathway for the motion of the forming tool. In this case MasterCAM 9.0 software was utilized to generate desired pathway. This software is commonly used for material removal in milling process and is suitable for ISMF operation, because it has built-in feature for path generation which can be successfully utilized for guiding the forming tool. The conical model maximum depth is 77 mm, top radius 130 mm, bottom radius 80 mm and forming angle 72°.

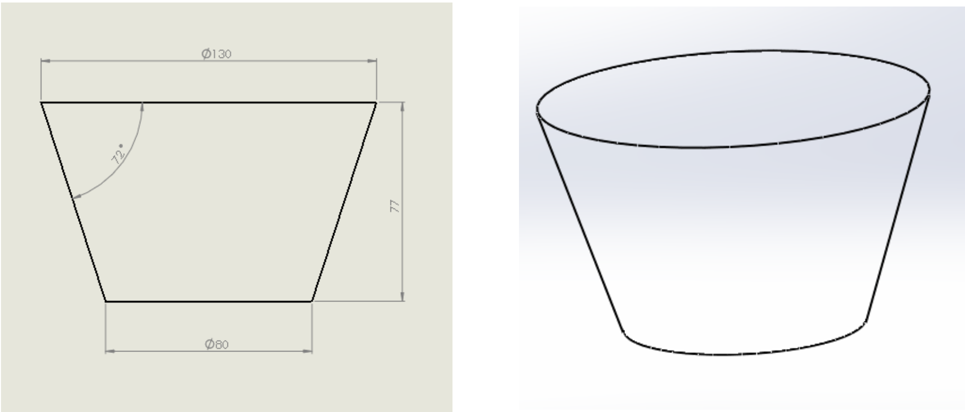


Figure 2.6. Conical geometry and its dimensions

For generation of the path, a spiral conical strategy was chosen. Here, the moving tool executes a conical spiral path with continuous contact with the sheet surface.

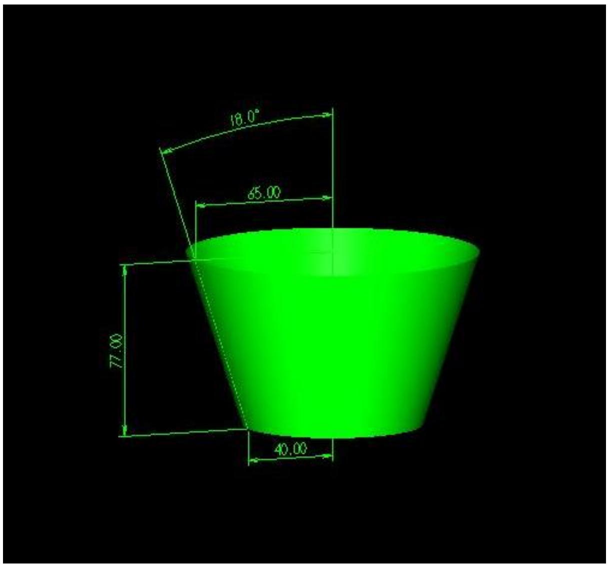


Figure 2.7. Model generated MasterCAM 9.0 software

For generation of tool path for illustrated Figure 2.7, the part itself is sliced into number of pieces and for each layer the contour of the part is found. Furthermore, the path is generated according the provided contour. It is important that different layers are connected in order to create continuous tool path for the process. The tool starts moving along the continuous single contour when touching the surface of the sheet. When single contour is done, vertical step down Δz is applied and the tool continues to move along next generated contour until the operation is finished.

2.6 Preparation of support

Aiming for reduction of deformation between surface and tool working region, and improvement of accuracy for the produced part additional support was used. Material of chosen support was wood plate with thickness of 12 mm and size of 270 x 270 mm. All necessary pieces was processed and prepared to be fitted in to the rack. The hole of 100 mm was made by milling operation with DMU 35M milling machine.

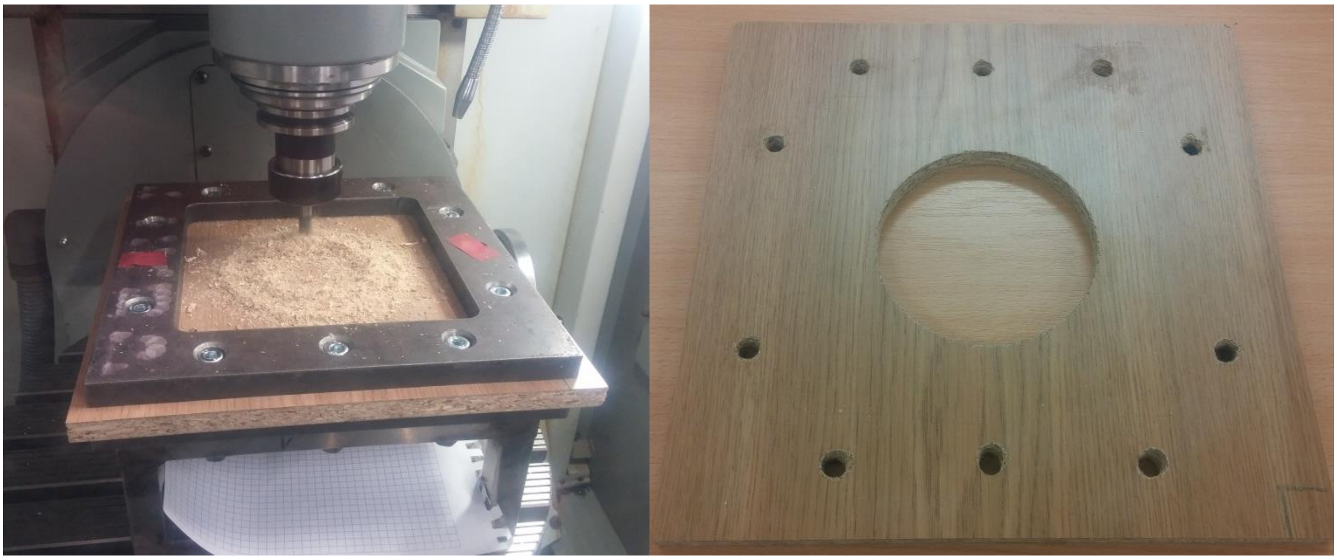


Figure 2.8. Preparation of the support

2.7 Sheet metal forming operation

Since the toolpath is generated and the support is prepared, the ISMF operation can be done. Fixture is assembled with the support and EN AW1050DDQ aluminium sheet. Knowing that there is lack of information regarding working regimes for this type of operation technological regimes were set experimentally. for this model: feed rate was 600 mm/min, plunge rate - 400 mm/min, retraction rate - 800 mm/min, spindle rotation speed – 400 rpm, vertical stepdown z - 0,7. Time for the process, generated by the program, was 45 min.

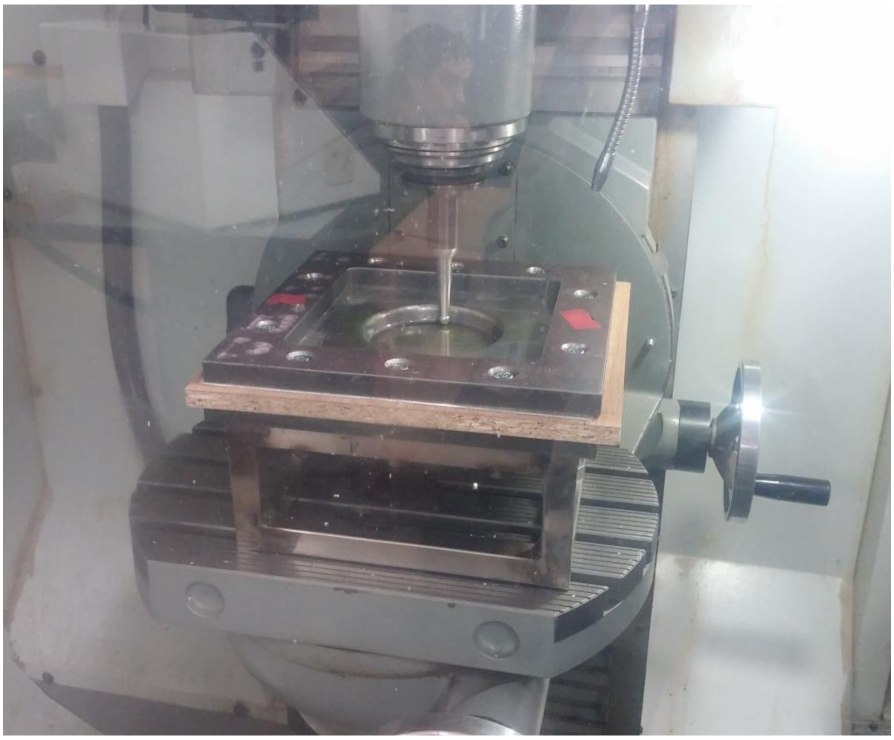


Figure 2.9. Forming process

Operation was done successfully and no fraction has occurred on the side walls of cone. Required dimensions were achieved. Precise dimensions will be measured utilizing CMM machine. Moreover, measurements of geometry of a part will be measured utilizing CMM machine.

2.8 Cost calculations for production

Manufacturing of sheet metal parts usually are produced with usage of does and punches. Shape and dimensions of required product can vary a lot depending on its complexity. This technology is suitable for mass production because cost of dies and punches decreases as number of parts increases. Following nowadays tendencies demanding of new products with small-batch size, various conventional methods are taken into account. Because of this reason incremental forming has gained great interest for simple tooling and flexibility.

Since demand in small-batches production is increasing whole production system has to be rearranged. Nevertheless, high flexibility rate and short lead times are important. Regarding the forming process, the following guidelines can be used for efficient low volume production: reduced lead – time for each product, reduced changeover time between products, reduced time and cos for development of manufacturing tool, lower time between different products by using flexible tooling [25].

Incremental sheet metal forming cost has been determined for a truncated cone that is shown in Figure 2.10.

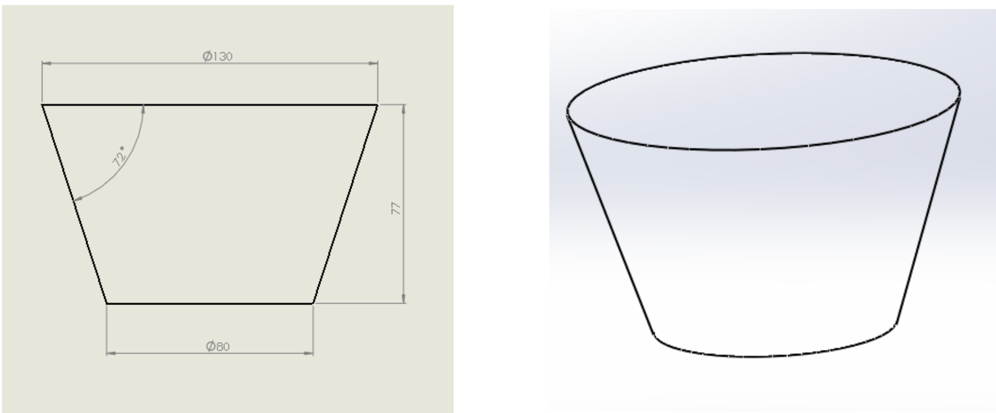


Figure 2.10. Model of a specimen

Parameters necessary for calculation are presented in Table 2.4. These parameters are determined individually and depends on used equipment for production.

Table 2.4. ISMF parameters for cost calculation

	ISMF
Personnel cost, EUR/h	20
Machine cost. EUR/h	30
CAM development, min	50
Setting up time, min	30
Part forming time, min	16

According to provided data in the Table 2.4, cost per part using incremental sheet metal forming operation can be calculated.

Total cost = (CAM development time)*(Personnel cost)+N*(Part forming time)*(Personnel cost)+N*(Part forming time)*(Machine cost)

Let N be number of parts and equal to 100.

Total cost = 0.5x20+100x0.16x70x100x0.16x30 = 810 EUR

Cost per part = 810 / 100 = 8.1 EUR

This calculation was done for a truncated cone. It should be noted that production cost can vary a lot and is highly dependent on product complexity where machining time can be increased significantly. It must be taken into account that the calculations can be stated as reference for production of other parts, but in every case recalculations should be done before further production.

3. RESULTS OF INVESTIGATION

3.1 Formability test of sheet with support and with no support

In order to produce a part with desired shapes it is necessary to examine formability properties, e.g. forming angle of aluminium AW1050DDQ. In this case two sets of experimental tests were carried out comparing formability of truncated cone with and with no support.

Furthermore, to determine forming angle several experiments were done by increasing drawing angle from 71° to 76° after every experiment. Depth of specimens varies from 77 to 100 mm. For lower forming angles vertical stepover was set to 0,2 mm per full pass. All parameters of experimental analysis are presented in Table 3.1 and Table 3.2

.

Table 3.1. Experimental analysis of working parameters with no support

No of experiment	Feed, f (mm/min)	Spindle speed, S (RPM)	Plunge rate (mm/min)	Drawing angle β, (°)	Forming depth, h (mm)	Stepover, ΔZ (mm)	Time duration T, min	Status
1	600	400	400	71	100	0,2	45	No fracture
2	600	400	400	72	77	0,2	16	No fracture
3	600	400	400	73	82	0,2	17	No Fracture
4	400	400	300	74	88	0,1	35	Fracture at 45 mm
5	400	400	300	74	88	0,1	35	Fracture at 75 mm
6	400	400	300	75	93	0,05	56	No fracture
7	400	400	300	76	40	0,05	59	Fracture at 35 mm

Results of performed experiments and values of working regimes during the experiment are graphically illustrated in Figure 3.1.

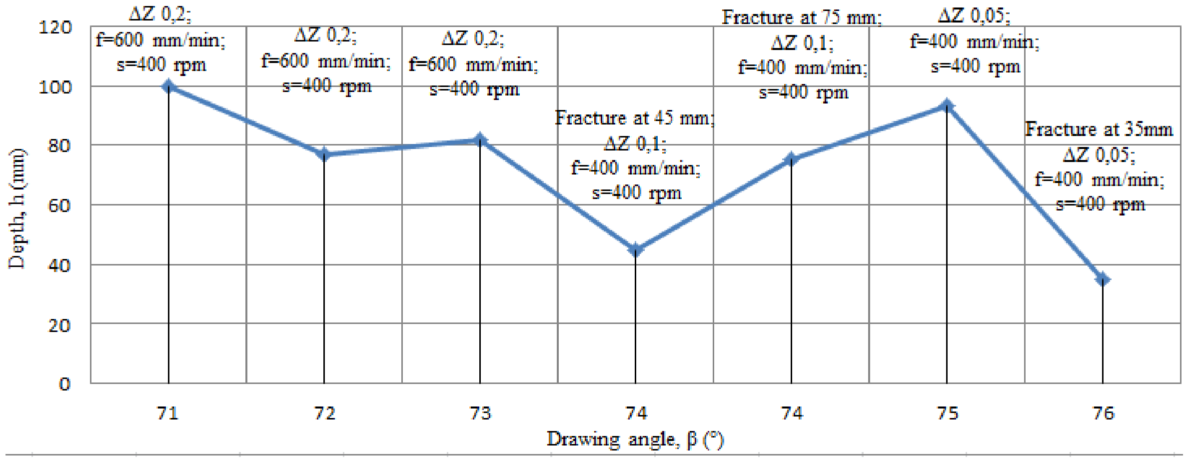


Figure 3.1. Parameters of forming AW1050DDQ without support

Second part of experimental data is presented in Table 3.2. Experiments with contact angle of 71° - 76° was done using wood support. Support was formed according to top diameter of truncated cone.

Table 3.2. Experimental analysis of working parameters with support

No of experiment	Feed, f (mm/min)	Spindle speed, S (RPM)	Plunge rate (mm/min)	Drawing angle β, (°)	Forming depth, h (mm)	Stepover, ΔZ (mm)	Time duration T, (min)	Status
1	600	400	400	71	100	0,2	45	No fracture
2	600	400	400	72	77	0,2	16	No fracture
3	600	400	400	73	82	0,2	17	No Fracture
4	400	400	300	74	88	0,1	35	No fracture
6	400	400	300	75	93	0,05	56	No fracture
7	400	400	300	76	40	0,05	59	Fracture at 20 mm

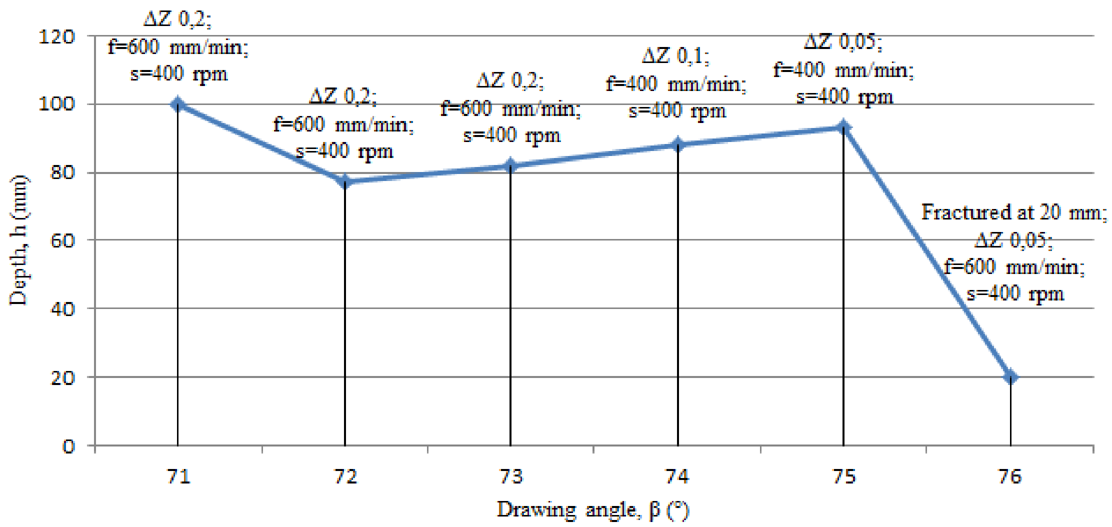
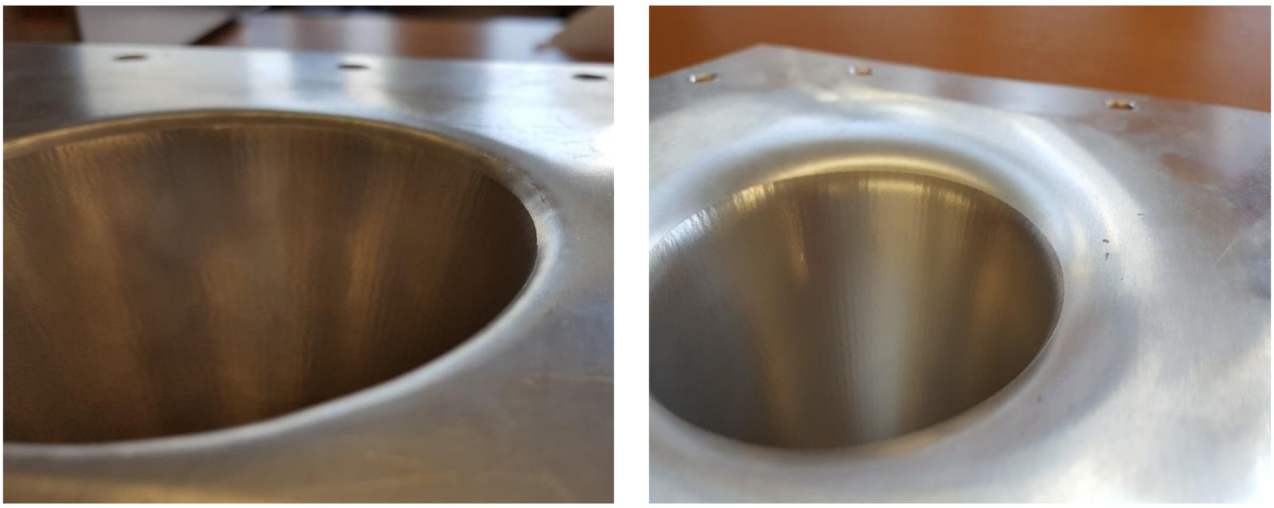


Figure 3.2. Parameters of forming AW1050DDQ with support

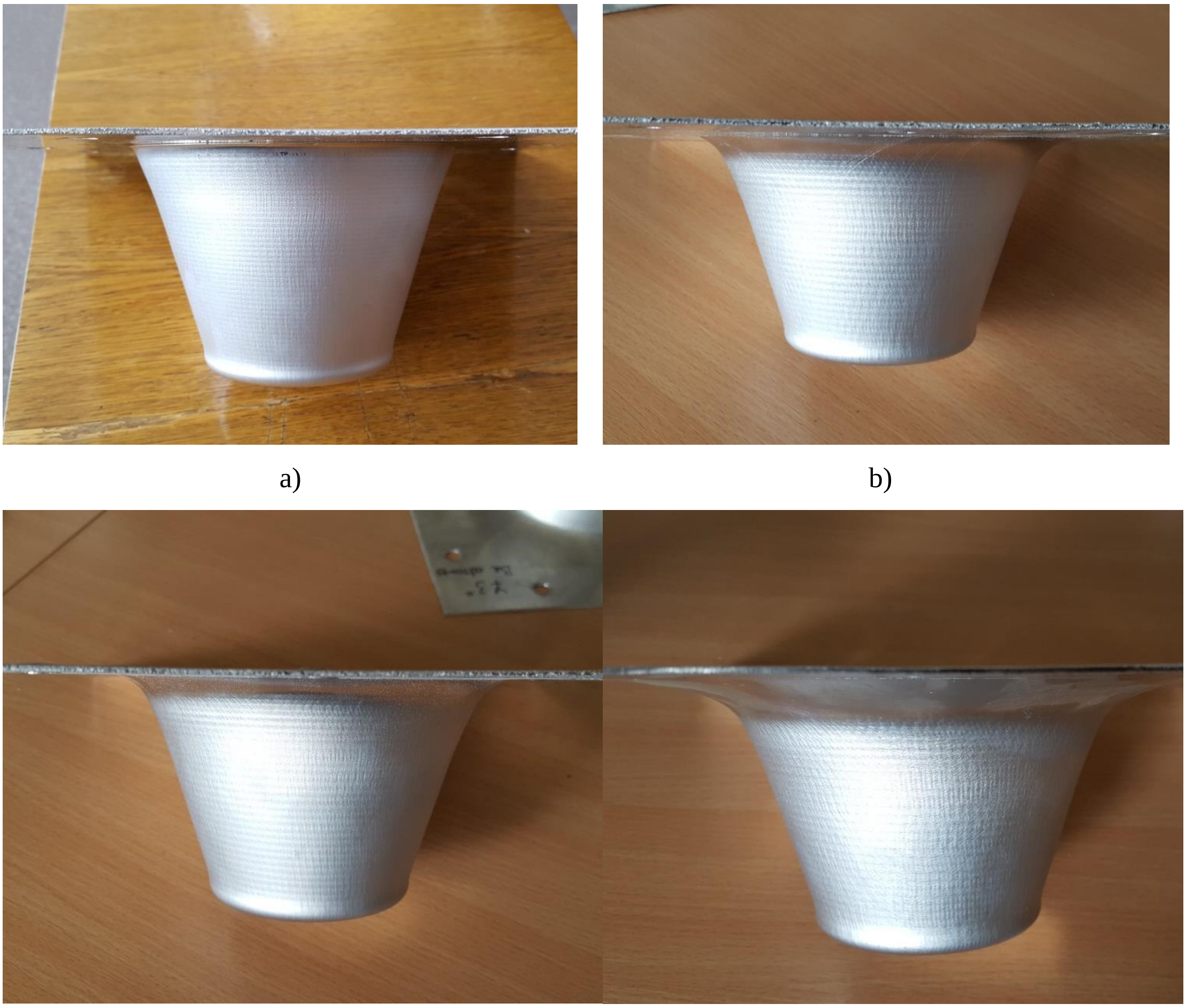
According to the data present in Figure 3.1 and Figure 3.2, it can be stated that both experiments were successful with forming angle of 71°, forming depth of 100 mm was reached and no fracture occurred during the process. Deformation of forming edge that occurs between contact surface of the blank and working point when tool is applied with force is significantly reduced and is clearly visible. Both tested parts are presented in Figure 3.3.



a) b)

Figure 3.3. Formed parts with drawing angle 71°: a) part formed with support, b) part formed without support

Second experiment was done using the same working regimes. Nevertheless, drawing angle for specific shape was increased to 72° and 73°. In both cases depth of 77 mm and 82 mm was reached. No fractures occurred.



a) b) c) d)

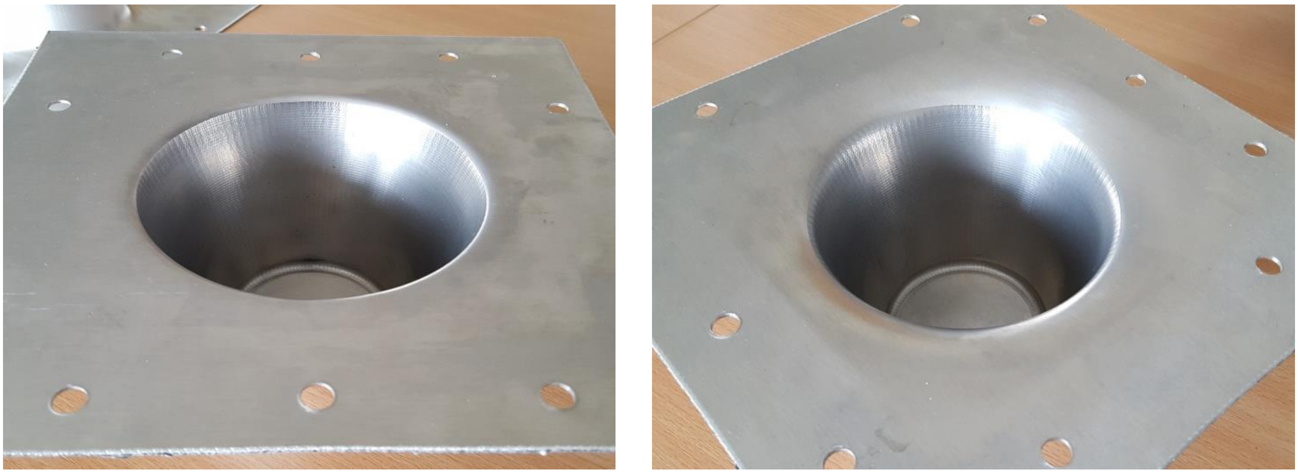
Figure 3.4. Conical shape formed parts during the experiment: a) 72° drawing angle with support, b) 72° drawing angle with no support, c) 73° drawing angle with support, d) 73° drawing angle with no support

In this part of experimental analysis two fractures occurred during forming process without support. Contact angle was increased to 74°. First time fracture occurred at 45 mm and second time at 75 mm when needed depth was 88 mm. Moreover, in both cases working regimes was the same: ΔZ – 0,1 mm, feed rate f = 400 mm/min, spindle speed s = 400 rpm. Lack of lubrication may be one of the reasons why specimen cracked on the sidewall, because another experiment with support was done successfully.

a) b)

Figure 3.5. Fractured cones with contact angle of 74° at different depths: a) fracture at 45 mm, b) fracture at 75 mm

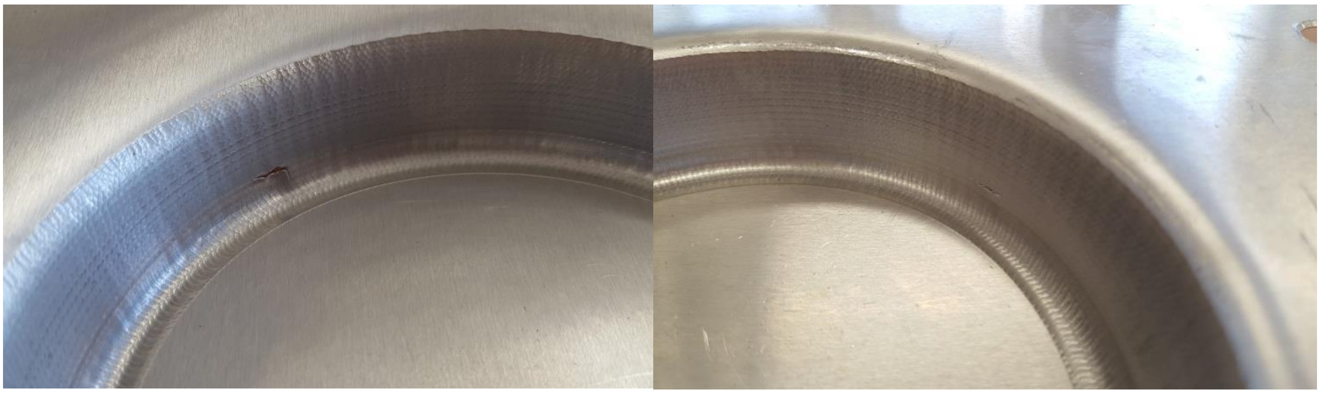
After several experiments it was decided to reduce vertical stepdown ΔZ to 0.05 due to increased forming angle to 75° and higher chance of fracture. Because of reduction of stepover time of the operation increased to 56 min. However, working regimes was set properly, so the cone was formed successfully and reached depth of 93 mm (Figure 3.6).



a) b)

Figure 3.6. During experiment formed two parts: a) 75° drawing angle with support, b) 75° drawing angle with no support

The last experiment was an attempt to reach maximum formability with angle of 76° and size of stepover was used the same as in previous case. When performing experiment without support fracture occurred at 35 mm depth. Experiment with support showed that forming process failed at 20 mm depth. Nevertheless, support restricts blank sheet and it remains in its primary position, so fracture occurs earlier when comparing with experiment when no support was used.



a) b)

Figure 3.7. During experiment formed truncated cone with drawing angle 76°: a) without support, b) with support

According to the experimental analysis results it was acquired that maximum forming angle for aluminium sheet material AW1050DDQ with 1,5 mm thickness is 75° for both cases. Moreover, deformation between material surface and contact region was reduced due to usage of rigid support and can be easily noticed (Figure 3.8 and Figure 3.9)

Figure 3.8. Formed cone with reduced deformation of surface

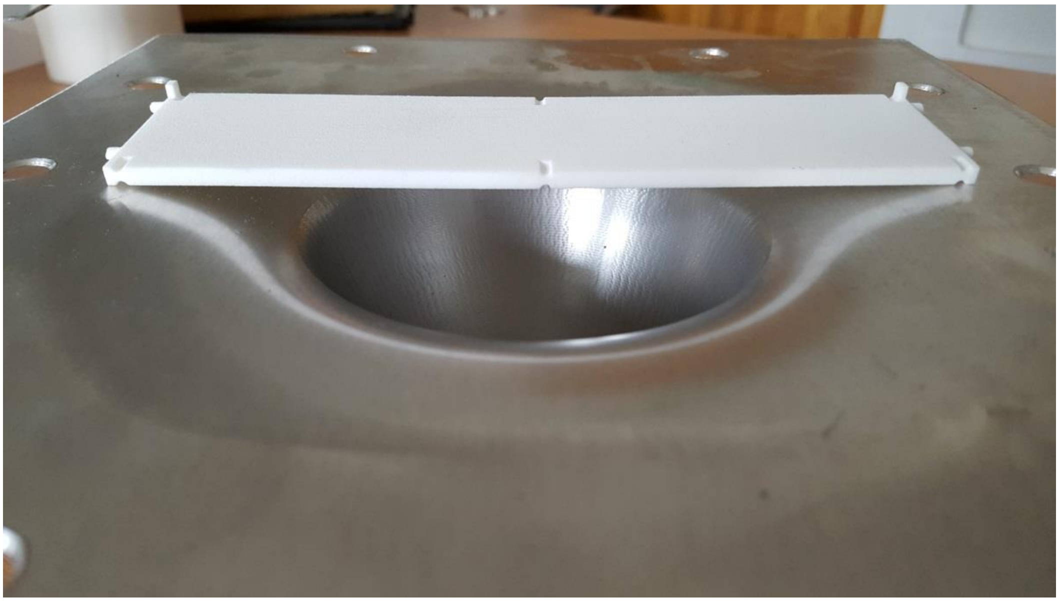


Figure 3.9. Formed cone with higher deformation

Furthermore, it was identified that drawing angle β was influenced by vertical stepdown size ΔZ since it was reduced. Basically, it can be stated that formability increased when stepover size ΔZ is lowered. Due to this reason necessary time to produce finished product increased.

3.1.1 CMM measuring machine

In order to precisely determine values of forming angle, height between top and bottom surfaces and deformation height between blank material surface and contact region, CMM machine was used. In this case DEA GLOBAL Silver Performance measuring machine was utilized (Figure 3.10).

High accuracy and throughput make the DEA GLOBAL Silver Performance suitable for most measuring applications, from prismatic parts up to parts with complex geometries and free-form surfaces. Multi-sensor technology offers the appropriate probing configuration – no matter if single-point measurements, high accuracy scanning or reverse engineering operations are needed. A full range of tactile and non-contact sensors is available [25].

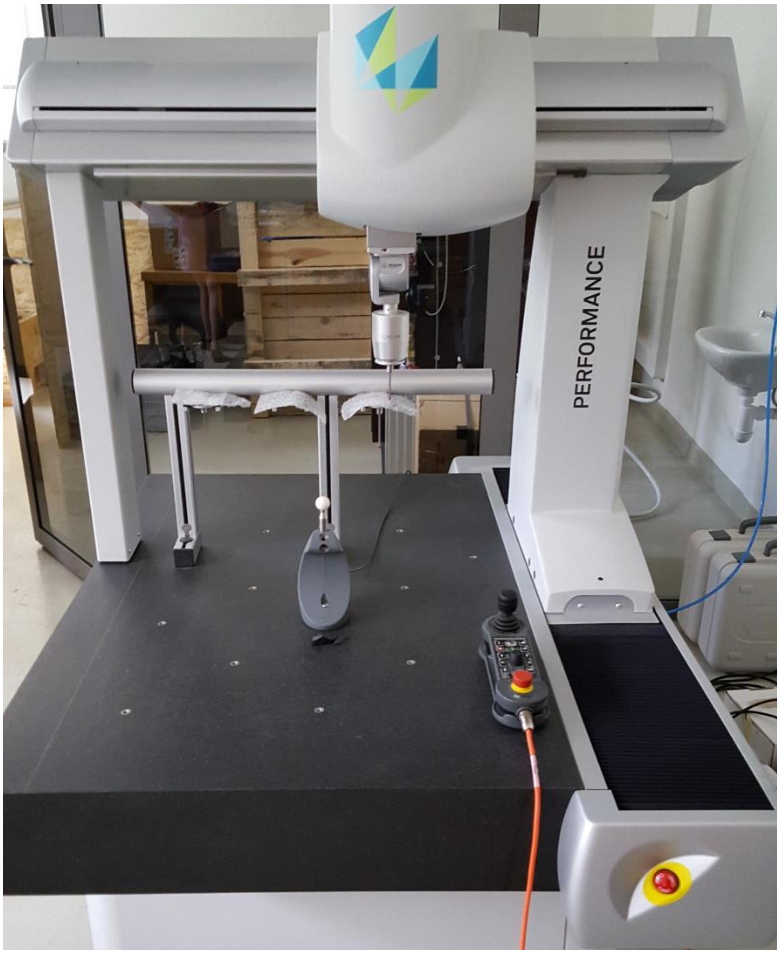


Figure 3.10. DEA GLOBAL measuring machine

Features and benefits of the machine [25]:

- First class accuracy and dynamics;
- State-of-the-art scanning throughput;
- Wide range of tactile and non-contact sensors for a multitude of applications;
- PC-DMIS Adaptive Scanning to reach best scanning performance by a few clicks;
- All-aluminium ultra-rigid frame;
- Patented TRICISION design with triangular cross section which provides optimum stiff-to-mass ratio for unquestioned precision and long-term stability;
- High-rigidity large-section Z spindle optimises the use of vertically extended tooling;
- High-resolution scales;
- One-piece table construction, patented dovetail guide ways are precision-machined in granite to improve accuracy and repeatability;
- Ergonomic and intuitive-to-use icon-based Universal JogBox, optional PC-DMIS interactivity for optimised workflow operations;

- CLIMA structural temperature compensation (16 – 26 °C);
- Minimum footprint for easy fit in tight spaces.

Technical data of DEA GLOBAL Silver Performance coordinate measuring machine is given in Table 3.3:

Table 3.3. Technical data of DEA GLOBAL Silver Performance machine [26]

Measuring range, mm		
X	Y	Z
500	500 - 700	500
700	700 - 1000	500 – 660
900	1200 – 1500 - 2000	800
1200	1500 – 2200 - 3000	1000
Accuracy: MPE_E = from 1.5 + L/333 µm		

3.1.2 Software

In order to successfully control coordinate measuring machine (CMM) special software is required. PC-DMIS CMM is the world's leading CMM software. Powerful capabilities allows to measure parts from simple prismatic parts to very complex components from aerospace or automotive fields. Measurement process window is presented in Figure 3.11.

PC-DMIS CMM leads the way in revolutionizing CMM measurement. It was the first CMM software to [27]:

- Use CAD models in the inspection process;
- Directly link CAD systems and measurement software through its Direct CAD interface (DCI) technology;
- Implement a full set of sheet metal measurement routines tailored for the automotive industry;
- Digitally simulate measurement in an offline virtual CMM environment;
- Easily align complex, contoured parts using our breakthrough iterative alignment technology.

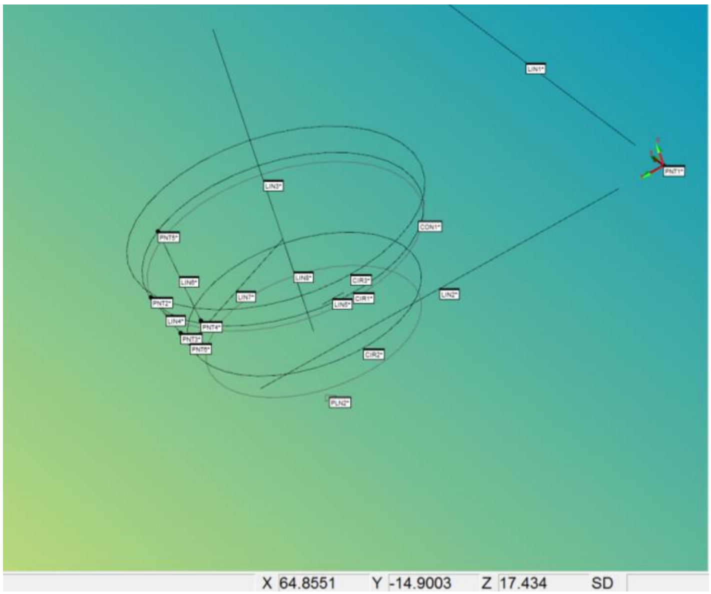


Figure 3.11. PC – DMIS software interface

Three measuring probes with different length and tip diameter were available. In our case 3 mm measuring probe was used and is presented in Figure 3.12.

Figure 3.12. Measuring probe of the CMM machine

3.1.3 Sequence of measurement

To perform further measurements of produced specimens it is necessary to follow sequence of actions in order to find needed values precisely.

Firstly, alignment of a part must be done. Here it is required to describe one plane (PL1) by touching with probe the surface of a part three times and two lines (LN1, LN2) by putting two points in x and y axes (Figure 3.13). After x and y axes are know it was necessary to find their intersection point. This allowed describing parts position in three dimensions – x, y and z.

Secondly, in order to measure height of a part it was required to describe second plane (PL2) and this was done as explained previously. Furthermore, to form a cone it was needed to lay three points on inside surface of a cone at two different heights (CIR1, CIR2). After this operation contour of a cone was created successfully in virtual environment.

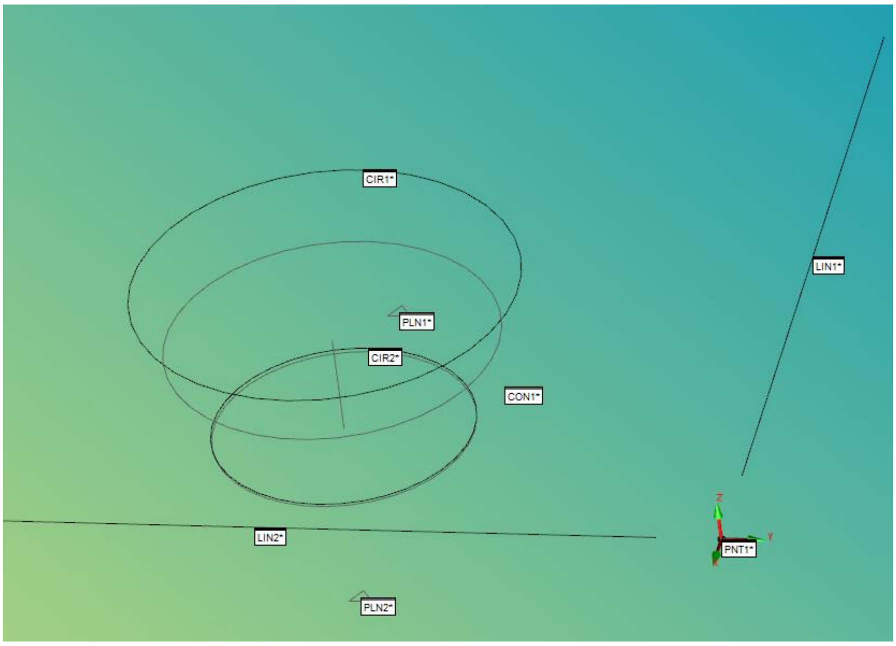


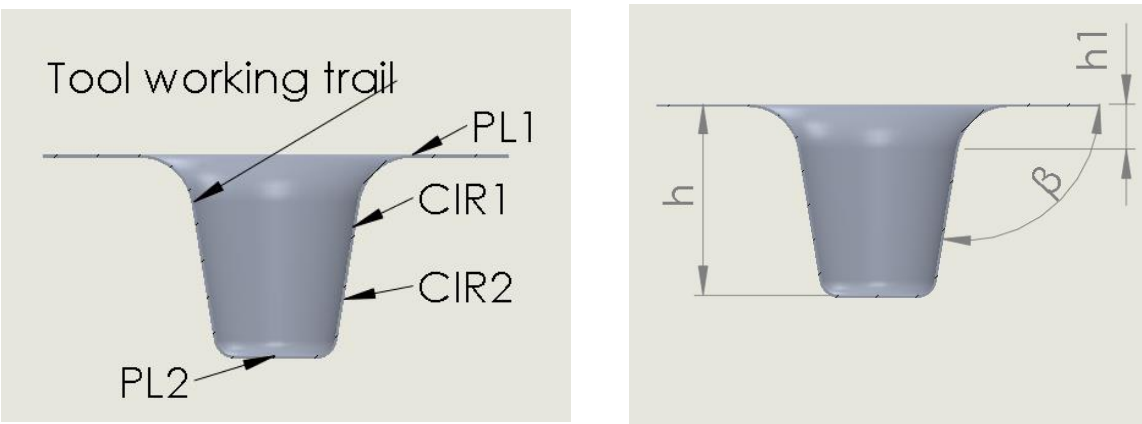
Figure 3.13. Points of a measured part displayed in PC – DMIS interface

Figure 3.14. Measurement process of a truncated cone

Measurement process was carried out for all produced specimens and allowed to compare results of parts that were made with support and with no support.

3.2 Geometrical accuracy test

Measurement was done successfully and data for each sample was obtained. Three main values were investigated: height difference between planes (h), drawing angle (β) and deformation height (h1) occurred between plane (PL1) and point where first tool pass was done.



a) b)

Figure 3.15. Sketch of a specimen with noted sections for measurement

Obtained data for parts with support and with no support is presented in Table 3.4 and Table 3.5.

Table 3.4. Data obtained after measurement of parts with support

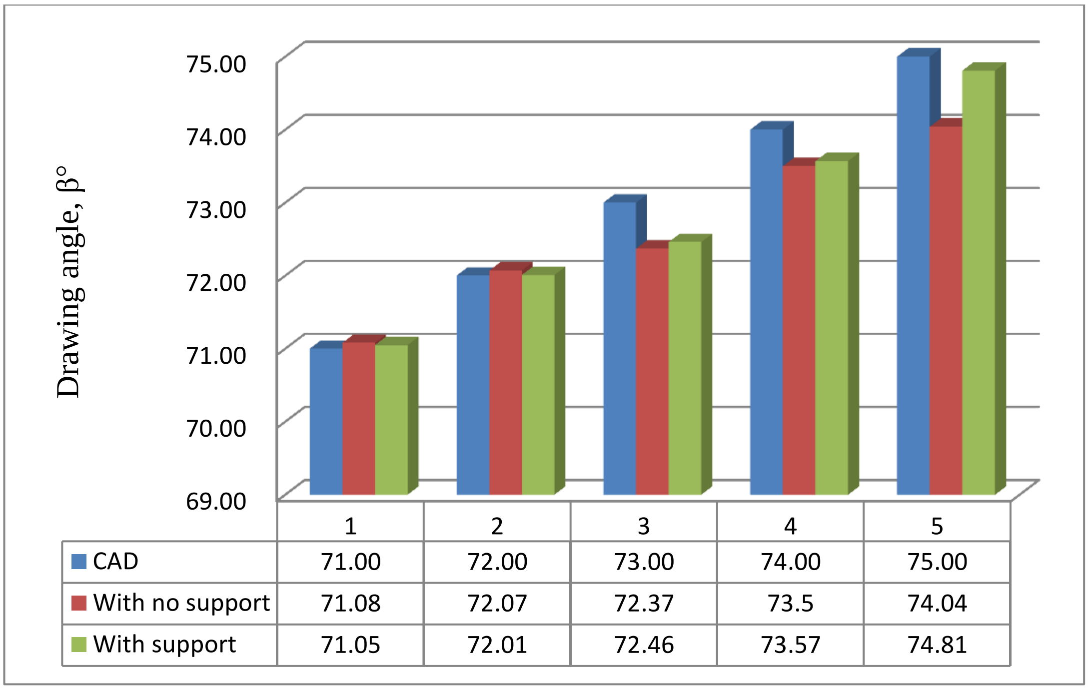
No of experiment	Angle, β°	Height, mm	With support		
			h, mm	h1, mm	β°
1	71	100	103,82	1,56	71,05
2	72	77	80,99	3,92	72,01
3	73	82	86,26	4,58	72,46
4	74	88	92,43	1,39	73,57
5	75	93	97,52	1,29	74,81
6	76	40	24,64	1,77	-

It is important to notice that parts with drawing angle 72° and 73° was produced with higher clearance between sidewall of cone and hole of support which was 3 mm from each side when in other cases clearance was 1,5 mm, so because of this h1 increased. For specimen with angle 76° real value of angle was not measured due to occurred fraction.

Table 3.5. Data obtained after measurement of parts with no support

No of experiment	Angle, β°	Height, mm	With no support		
			h, mm	h1, mm	β°
1	71	100	100,29	8,75	71,08
2	72	77	80,44	8,69	72,07
3	73	82	85,48	9,02	72,37
4	74	88	87,21	8,62	73,5
5	75	93	97,52	8,54	74,04
6	76	40	30	8,91	-

Comparison of drawing angle with and with no support was done and is presented in Figure 3.16. Blue bar represents nominal values of drawing angle in CAD, red bar illustrates test results that were obtained with no support and green bar shows results of measurement when support was applied. According data it can be stated that lower angle deviations were obtained in experiments with support comparing with nominal values. Lowest deviation was reached in second experiment. Here nominal value according CAD was 72° and obtained result was 72,01°. Highest inaccuracy was in third experiment. Obtained value of part after test was 72,46° and nominal value was 73°. However, inaccuracy may be increased due to higher clearance between support and test piece.



	1	2	3	4	5
CAD	71.00	72.00	73.00	74.00	75.00
With no support	71.08	72.07	72.37	73.5	74.04
With support	71.05	72.01	72.46	73.57	74.81

Figure 3.16. Drawing angle deviation

After analysis it was clear that depth (h1) between contact plane (PL1) and tool working trail point was reduced when support was applied and schematically presented in Figure 3.17. According measured data it can be seen that deformation height in experiments with no support varies from 8,54 mm (75°) to 9,02 mm (73°). Experiments showed that application of support reduced deformation values and varies from 1,29 mm (75°) to 4,58 mm (73°) respectively. It is important to notice that value of deformation with support was increased due to higher clearance between support contour and sheet surface.

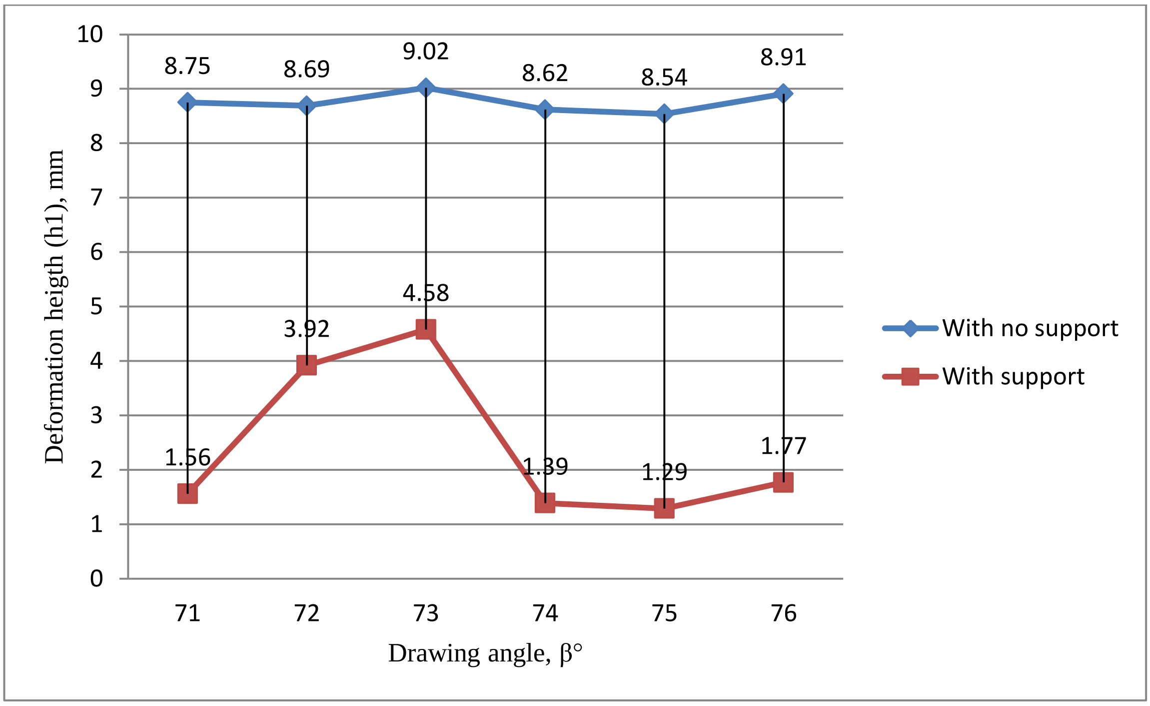


Figure 3.17. Contact angle vs depth of deformation (h1) in incremental forming with and with no support

Application of support allowed reducing deformation maintaining sheet material in its initial position during the experiments and higher geometrical accuracy was achieved.

To conclude, ISMF with additional support can be used to produce complex and more precise parts and prototypes. Usage of wood support was efficient and allowed to reduce geometrical deformation during the process.

CONCLUSIONS

1. Experimentally determined, that incremental sheet metal forming technology can be applied for production of prototypes. Quality of produced prototype depends on tool speed, size and path, lubrication, stepdown size and drawing angle. Forming angle can be increased by reducing forming regimes and production time increases respectively.
2. Equipment for the process was obtained is contained of forming tool, fixture for blank material processing and additional support.
3. Experimental tests were carried out by producing six prototypes with support and with no support with drawing angle 71°-76°. In case with additional support nu visible cracks occurred. However, in case with no support failure occurred during the process when drawing angle was 74°. It can be stated that reason of failure may be lack of lubrication. In cases with angle 76° cracks occurred in both experiments at depth 20 mm with support and 35 mm with no support, here nominal value was 40 mm.
4. Forming angle and size of deformation was determined precisely using CMM measuring machine. It was observed that drawing with support is more precise comparing to nominal values. Best result of drawing angle was achieved during experiment with drawing angle 72° and obtained value was 72,01°. Lowest value of drawing angle was achieved in experiment with 75° drawing angle when obtained result with no support was 74,04°. Height of deformation (h1) was also reduced. Lowest value achieved with support was 1,29 mm and highest value with support was 4,58 mm. Deformation value of support increased due to higher clearance between support and sheet material.

LITERATURE

1. Review of Incremental Forming of Sheet Metal Components. Internet access: http://www.ijera.com/papers/Vol3_issue5/I353951.pdf [Accessed on 2016.01.18]
2. Formability limits by fracture in sheet metal forming. Internet access: http://www.sciencedirect.com/science/article/pii/S0924013614000752 [Accessed on 2016.01.18]
3. Jeswiet, J.; Micari, F.; Hirt, G.; Bramley, A.; Duflou, A.;Allwood, J. "Asymmetric single point incremental forming of sheet metal", CIRP Annals - Manufacturing Technology 2005, 54 (2), 88–114.
4. Manufacturing of Sheet Metal Flanged Parts Using Multi-stage SPIF. Internet access: http://www.researchgate.net/profile/PAF_Martins2/publication/257366226_Manufacturing_of_Sheet_Metal_Flanged_Parts_Using_Multi-stage_SPIF/links/004635251a8fdcf3f9000000.pdf [Accessed on 2016.01.18]
5. Jeswiet, J. .; Micari, F.; Hirt, G.; Bramley, A.; Duflou, A.;Allwood, J. "Asymmetric Single Point Incremental Forming of Sheet Metal", CIRP Annals - Manufacturing technology, 2005, 54(2), 623-649
6. H. Meier, B. Buff, R. Laurischkat, V. Smukala "Increasing the part accuracy in dieless robot-based incremental sheet metal forming" CIRP Annals - Manufacturing Technology 58 (2009) 233–238
7. Influence of mechanical properties of the sheet material on formability in single point incremental forming. Internet access: http://www.sciencedirect.com/science/article/pii/S0007850607606805 [Accessed on 2016.01.18]
8. Theory of single point incremental forming. Internet access: http://www.sciencedirect.com/science/article/pii/S0007850608001248 [Accessed on 2016.01.18]
9. On the Behaviour of the Process and Material in Incremental Sheet Forming. Internet Access: https://aaltodoc.aalto.fi/bitstream/handle/123456789/13356/isbn9789526057194.pdf?sequence=1 [Accessed on 2016.01.18]
10. G. Hussain, H. Khan, L. Gao, N. Hayat, "Guidelines for tool size selection for single point incremental forming of an aerospace alloy", Materials and Manufacturing Processes, 2013, 324-329
11. Kim, J. Park, "Effect of Process Parameters on formability in incremental forming of sheet metal", Journal of Materials Processing Technology, 2002, 130-13, 42-46.

12. Bramley, A.N., 2001, "Incremental Sheet Forming Process for Small Batch and Prototype Parts", 2001, ISBN 3-87525-149-0, pp 95-102.
13. Asymmetric Single Point Incremental Forming of Sheet Metal. Internet Access: http://www.sciencedirect.com/science/article/pii/S0007850607600213 [Accessed on 2016.01.18]
14. Contact CAD CAM CNC Programming Services Internet Access: http://cncprogramming.martinchick.com/ball_mill_finish.html [Accessed on 2016.01.18]
15. Process window enhancement for single point incremental forming through multi step toolpaths. Internet Access: http://www.researchgate.net/profile/Hugo_Sol/publication/245226913_Process_window_enhancement_for_single_point_incremental_forming_through_multi-step_toolpaths/links/53eda7910cf26b9b7dc5f1e8.pdf [Accessed on 2016.01.18]
16. Jadhav S., G.R., Homberg W., Kleiner M., "Process Optimization and control for incremental forming sheet metal forming, 2003, Slovenia. p. 165-171.
17. Silva, M.B.C.d.J., Single Point Incremental Forming, in Mechanical Engineering December 2008, University Technical of Lisbon. p. 43.
18. Single Point Incremental Forming and Multi-Stage Incremental Forming on Aluminium Alloy 1050. Internet Access: http://repositorio-aberto.up.pt/bitstream/10216/72577/1/000157954.pdf [Accessed on 2016.01.18]
19. Single point incremental forming for facial implant. Internet Access: http://paginas.fe.up.pt/~falves/ISF%20JLino.pdf [Accessed on 2016.01.18]
20. Numerical simulation and experimental investigation of incremental sheet forming with an elastic support. Internet Access: http://link.springer.com/article/10.1007/s00170-014-6117-8 [Accessed on 2016.01.18]
21. ISEKI, H., "Flexible and Incremental Bulginf of Sheet Metal Using High-Speed Water Jet", JSME International Journal, 2001. 44(No.2): p. 486.
22. Modelling of Contact and Friction in Deep Drawing Processes. Internet Access: http://doc.utwente.nl/36538/1/t0000019.pdf [Accessed on 2016.01.18]
23. Milling machine DMU 35M. Available online: http://trademachines.de/assets/media/content/sites/3/2015/09/Deckel-Maho-DMU35M.pdf [Accessed on 2016.01.18]
24. Aluminium AW1050DDQ. Available online: http://www.aluland.com/en/x/30/chemical-composition [Accessed on 2016.01.18]

25. Small batch size sheet metal products manufactured by single point incremental forming process. Available online:

https://www.researchgate.net/publication/265269073_SMALL_BATCH_SIZE_SHEET_METAL_PRODUCTS_MANUFACTURED_BY_SINGLE_POINT_INCREMENTAL_FORMING_PROCESS_ECONOMIC_ANALYSIS [Accessed on 2016.05.18]

26. DEA GLOBAL Silver Performance. Available online. http://www.dea.it/DEA-GLOBAL-Silver-Performance_541.htm#.VzoDgbiLTZ4 [Accessed on 2016.05.18]
27. PC – DMIS CMM. Available online: http://hexagonmi.com/products/software/pc-dmis/pcdmis-cmm-388 [Accessed on 2016.05.18]