THESIS ON MECHANICAL AND INSTRUMENTAL ENGINEERING E34

Rapid Prototyping of Sheet Metal Components with Incremental Sheet Forming Technology

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

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MEELIS POHLAK

ABSTRACT

In modern manufacturing industry flexibility of production technologies is constantly gaining importance. Traditional forming processes use sophisticated and specialized tooling. The design and production of the tooling is time consuming and expensive. In recent few years new flexible sheet metal forming technique, called incremental sheet forming, has been introduced. It is based on layered manufacturing principle, where simple spherical tool that is moved along numerically controlled toolpath; deforms the sheet incrementally section after section. The part is produced by deforming the sheet locally. Two basic approaches of incremental sheet forming exist, forming with support and forming without support. The process is very flexible; it does not require expensive tools.

In the current thesis incremental sheet forming technology has been studied. The aim of current thesis is to investigate the mechanics of incremental sheet forming processes, and find ways to improve the process. In order to investigate the process, finite element analysis and experimental study have been performed. Finite element analysis was performed with two different software systems. Both used thin shell elements, non-linear material models and contact calculation. The results were validated with experiments. It was found that the simulation of full forming process is too time consuming to be used in everyday engineering work. However, forming forces can successfully be predicted with simplified models.

Some aspects of forming forces and formability were treated theoretically. Experiments for building forming limit diagrams were made.

Thorough experimental studies for investigating the influence of important product and process parameters to some process indicators with both approaches of incremental sheet forming were made. The models for predicting the indicators were built.

The implementation of the forming technology was discussed; some case-studies were made. Recommendations concerning manufacturability and part design were given.

Keywords: Incremental Forming; Sheet Metal Forming; Metal Forming Simulation; Rapid Prototyping; Experimental Study

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Meelis Pohlak

CONTENTS

SYMBOLS

Symbol	Unit	Comment
A	mm^2	Cross section area of the deformed strip
c_1, c_2		Material parameters characterizing formability
E	N/mm^2	Elastic modulus
e_{fd}	mm	Form deviation
e_f	mm	Flatness
f	mm/min	Feed rate
F_s	N	Stretching force, the force applied to sheet blank in Incremental Forming with support
F_t	N	Tensile force
F_x	N	Force in x-axis direction
F_y	N	Force in y-axis direction
F_z	N	Force in z-axis (vertical) direction
K		Strength coefficient
L	mm	Length of toolpath
m		Exponent in Hill's non-quadratic yield criterion
n		Strain hardening exponent
p_z	mm	Vertical step size of the forming tool
R	mm	Radius of the spherical forming tool
R_a		Anisotropy parameter
SR	µm	Surface roughness
Z		Function of principal stress ratio
t	mm	Sheet thickness
t_0		Initial sheet thickness
α	Degree	Wall draft angle
σ_b		Yield stress in equi-biaxial tension
σ_1	N/mm^2	Maximal principal stress
σ_t	N/mm^2	Stress component in the thickness direction
σ_x	N/mm^2	Stress component in x-axis direction
σ_y	N/mm^2	Stress component in y-axis direction
σ_z	N/mm^2	Stress component in z-axis (vertical) direction
$\overline{\sigma}$	N/mm^2	Equivalent stress
ε_t		Strain component in the thickness direction
ε_w		Strain component in width direction
ε_1		Major principal strain
ε_2		Minor principal strain
ε_x		Strain component in x-axis direction
ε_y		Strain component in y-axis direction
ε_z		Strain component in z-axis direction
$\overline{\varepsilon}$		Equivalent strain

ε^{fr}		Fracture strain
$\bar{\varepsilon}^{fr}$		Equivalent fracture strain
$\bar{\varepsilon}^{P}$		Effective plastic strain increment
ψ		Indicator of risk of necking
ρ	kg/m^3	Density
θ	Degree	Contact angle
υ		Poisson’s ratio

ABBREVIATIONS

ANOVA – Analysis of Variance
CAD – Computer Aided Design
CAE – Computer Aided Engineering
CAM – Computer Automated Manufacturing
CMM – Coordinate Measuring Machine
CNC – Computer Numerical Control
DOE – Design of Experiments
FEA – Finite Element Analysis
FEM – Finite Element Method
FLC – Forming Limit Curve
FLD – Forming Limit Diagram
IF – Incremental Forming
ISF – Incremental Sheet Forming
MDF – Medium Density Fiberboard
MPF – Multi-Point Forming
NC – Numerical Control
PC – Personal Computer
RP – Rapid Prototyping
SPF – Single Point Forming
SPIF – Single Point Incremental Forming
TPIF – Two Point Incremental Forming
2D – Two Dimensional
3D – Three Dimensional

LIST OF PUBLICATIONS

The main results of the research have been published in several journal papers and presented on different conferences. The research papers published in international peer-reviewed journals are as follows:

1 Pohlak, M., Küttner, R., Majak, J. Modelling and optimal design of the incremental forming process. Proceedings of the Estonian Academy of Sciences, Engineering. 2004, vol. 10, no. 4, pp. 261–269.

2 Pohlak, M., Küttner, R., Majak, J. Modelling and optimal design of sheet metal RP&M processes, Rapid Prototyping Journal, vol. 11, no. 5, 2005, pp. 304–311.

3 Majak, J., Pohlak, M., Küttner, R. A simple algorithm for formability analysis. Journal of Achievements in Materials and Manufacturing Engineering. 2007, vol. 22, no. 1, pp. 57–60.

4 Pohlak, M., Majak, J., Küttner, R. Incremental Sheet Forming Process Modelling – Limitation Analysis. Journal of Achievements in Materials and Manufacturing Engineering. 2007, vol. 22, no. 2, pp. 67–70.

5 Pohlak, M., Majak, J., Küttner, R. Manufacturability and Limitations in Incremental Sheet Forming. Proceedings of the Estonian Academy of Sciences, Engineering. 2007, vol. 13, no. 2, pp. 129–139.

The conference papers are as follows:

1. Pohlak, M.; Küttner, R.; Majak, J.; Karjust, K., Sutt, A. Simulation of incremental forming of sheet metal products. Proc. of 4th International DAAAM Baltic Conference, Tallinn, Estonia, 2004, pp. 149–151.
2. Pohlak, M.; Küttner, R.; Majak, J.; Karjust, K., Sutt, A. Experimental study of incremental forming of sheet metal products. Proc. of 4th International DAAAM Baltic Conference, Tallinn, Estonia, 2004, pp. 145–148.
3. Pohlak, M., Küttner, R., Majak, J. Simulation of incremental forming processes of sheet metal. Proc. of IIIrd International Conference on Advances in Production Engineering. Warsaw, Poland, 2004, pp. 133–140.
4. Küttner, R., Pohlak, M., Majak, J. Modelling and optimal design of sheet metal RP&M processes. Proc. of 10th European forum on rapid prototyping: Rapid prototyping and manufacturing, Paris, France, September 2004.
5. Pohlak, M., Majak, J., Küttner, R. Manufacturability Issues in Incremental Sheet Forming. Proc. of 5th International DAAAM Baltic Conference, Tallinn, Estonia, 2006, pp. 157–162.
6. Pohlak, M., Majak, J., Küttner, R. Incremental Sheet Forming Process Modelling – Limitation Analysis. Proc. of Mechanics and Materials in Design 2006 Conference, Porto, Portugal, 2006.

1 INTRODUCTION

In modern manufacturing industry, the general trend is towards the decrease of development period of new products. On the other hand, in order to satisfy different customers with different preferences, variety of products has to be offered. In addition, the design of products is becoming increasingly more complex and higher quality level has to be achieved.

In production engineering, parts made of sheet metal are widely used. For manufacturing of parts with conventional sheet metal forming techniques, for example deep drawing, dedicated tools are needed. They are highly specialized, expensive and time consuming to produce.

To provide more flexible alternative, new sheet metal forming methods have been studied. One special type of them is incremental sheet forming. It allows forming sheet metal parts with minimum preparation time and manual processing using universal CNC machining centre. Using this method, prototypes of new product made of sheet metal can be fabricated within few hours.

The author of the thesis is studying incremental sheet forming process since 2003, due to joining international project ProSheet (Prototyping and low volume production of sheet metal components), financed by Nordisk Industrifond (Lamminen, 2003). The project was kind of introductory, with the aim to map the state of the art in the field and the needs of Nordic European countries. Experts from Norway, Sweden, Finland and Estonia participated in this project.

After the end of the project ProSheet, investigation of incremental sheet forming technology in Tallinn University of Technology continued and is still in progress.

In current thesis incremental forming process is considered as a method of Rapid Prototyping using sheet metal materials. The main emphasis is on the flexibility of the process.

The thesis consists of five main chapters. In introduction, flexible sheet metal forming processes are described, followed by objectives and tasks of current thesis. The second chapter is dedicated to theoretical and numerical analysis. In this chapter, theoretical models for calculation of forming forces in incremental sheet forming, and also numerical analysis using Finite Element Method (FEM) of incremental sheet forming process with and without support are described. The third chapter presents experimental studies of incremental sheet forming process. Both, forming with and without support are covered. Next chapter provides recommendations for industrial implementation of the incremental forming process; case-study of successful use of the process is made. The last chapter presents general conclusions.

1.1 Overview of Rapid Sheet Forming Techniques

Rapid sheet forming process can be considered as a process where the emphasis lies on short set-up period of production. Therefore, the most important aspect is flexibility. Usually it is employed for prototyping and low series production (up to hundreds of parts).

To characterize the position of incremental sheet forming, the most important aspects of main more or less flexible sheet forming processes are described below.

1.1.1 Simple-pass Techniques

The techniques meant by the term "simple-pass techniques" are those, where the final form of workpiece is caused by simple movement (simple trajectory) of the tool (or forming environment).

Deep Drawing with Soft Tools or Rapid Tooling

Deep drawing is a metal forming process in which a sheet metal blank is radially drawn into a forming die by the mechanical action of a punch (see Fig. 1.1), so it is a shape transformation process with material retention. The flange region experiences a radial drawing stress and a tangential compressive stress due to the material retention property. These compressive stresses result in flange wrinkles. Wrinkles can be prevented by using a blank holder, the function of which is to facilitate controlled material flow into the die. The process generally requires presses with double action – force for blank holder and for punch (ASM, 2006).

Parts made by deep drawing usually need several successive draws and annealing operations between them (Boljanovic, 2004).

Depending on the production series and time constraints, tools can be made of solid steel and other metal alloys, concrete, wood, plastic materials, etc. The tools are usually machined, but for shorter preparation time, they can also be produced using rapid prototyping processes (e.g. laser sintering, stereolithography, etc.) or sheet laminating techniques (Mueller, 2000; Müller, 2001).

In a study, performed by Mueller, a comparison of different processes of tool preparation was made (Mueller, 2000). The cost of laminated tools (made of 0,5 mm steel sheets cut out with laser and stacked followed by NC milling) was reported only 38% of cost of tools made of solid steel by NC milling. However, the preparation time of laminated tools was 20% higher.

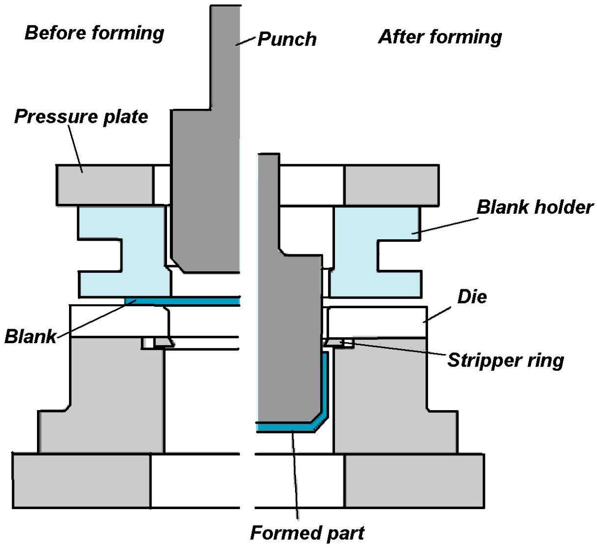


Fig. 1.1. Principle of deep drawing

The advantages are:

- Short forming cycle times
- Good accuracy
- Complicated shapes can be formed

The disadvantages are:

- Expensive equipment and tools
- Soft tools wear out quickly, and hard tools are expensive and time consuming to make
- The set-up of the process is time consuming and needs skilled workers

Forming with Flexible Materials

The forming with flexible material is also known as flexible-die forming. In this process, punch or die is replaced with flexible material – rubber, polyurethane, fluid or flexible diaphragm and fluid. One of the dies is eliminated, thus reducing the cost of making it. The solid tool is usually similar to the punch in the conventional die, but it can be the die cavity. The flexible material (rubber) acts similar to hydraulic fluid applying nearly equal pressure on all workpiece surfaces as it is pressed around the form block (ASM, 2006).

For forming with flexible materials, usually universal hydraulic presses can be used, except in some special cases. In some hydro forming processes, extra equipment is needed for better tool movement and pressure control.

The tool half used in the process can be made of epoxy resin, zinc alloy, hardwood, or other inexpensive material, as well as steel, cast iron and aluminum alloy (ASM, 2006).

Several different types of flexible die forming exist. Nowadays, the processes are categorized into three main groups: rubber-pad, fluid cell, and fluid forming (ASM, 2006; Boljanovic, 2004).

In rubber-pad forming (the simplest type), the rubber-pad retainer is fixed to the upper ram of the press (Fig. 1.2). The platen, containing the form block, is placed on the bed of the press. The blank is placed on the form block and is held in position by several locating pins. As the ram of the press descends, the rubber pad presses the blank around the form block, thus forming the workpiece. The rubber-pad retainer fits closely around the platen, forming an enclosure that traps the rubber as pressure is applied (ASM, 2006).

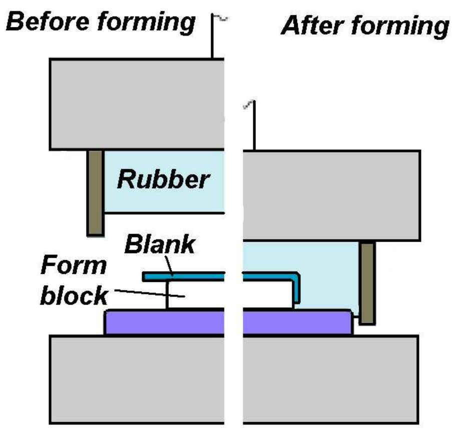


Fig. 1.2. Rubber-pad forming

In fluid-cell forming, the fluid-cell (a flexible container) is backed up by hydraulic fluid to exert a uniform pressure directly on the workpiece, located at the form block that is positioned on the press table (ASM, 2006).

In fluid forming, a rubber diaphragm serves as both the blankholder and the flexible die member. The fluid, pushed by upper ram of the press, exerts uniform pressure to the workpiece using rubber diaphragm. The process differs from rubber-pad forming and fluid-cell forming in that the forming pressure can be controlled as a function of the draw depth of the part (ASM, 2006).

Forming with flexible materials is usually used for producing moderately shallow, recessed parts, having simple flanges.

The advantages compared to conventional forming processes are (ASM, 2006):

- Only a single solid (metal) half of tool is required
- Tools can be made of low-cost, easily workable materials because of the hydrostatic pressure applied to the tools
- Shorter set-up time (no tools lining-up is needed)
- One rubber pad or diaphragm can be used with different die shapes
- Thinning of the sheet, as occurs in conventional forming, is reduced considerably

- Different metals and thicknesses can be produced in the same tool
- High quality surface finish – no tool marks are created

The disadvantages are (ASM, 2006):

- The production rate is slow – process is suitable primarily in prototyping and low-volume production
- The pad or diaphragm has limited lifetime (depending on the pressure and geometry of the parts to be formed)
- Lack of sufficient forming pressure causes less sharp geometry or even wrinkles

High-Velocity Forming

High-velocity forming methods include techniques such as explosive forming and electromagnetic forming. They are different from other metal forming methods in that the explosive or electromagnetic force first accelerates the workpiece to a high velocity, i.e. the kinetic energy of the workpiece is significant. The workpiece then changes its shape as it strikes against a die or as it is decelerated by plastic deformation. Thus, forming is largely inertial due to the dissipation of kinetic energy as plastic deformation.

Features of high-velocity sheet forming are as follows:

- Only one die is needed for forming
- High pressures act only a short period of time, so the inertia of tools is enough to hold them in place – light tooling can be used
- Inertial forces are dominating, while in conventional forming inertia can be ignored
- High pressures are easily created in high velocity contact
- Changes occur in constitutive behavior of metals under high strain rates
- New loading modes are possible – they can be combined with traditional forming tools (e.g. electromagnetic forming coils can be integrated into stamping tools)
- Formability can be improved – if loading and boundary conditions are properly chosen, ductility far beyond typical quasi-static ductility can be achieved
- More uniform strain distribution can be achieved
- Reduced wrinkling – inertial forces strongly suppress wrinkling
- Small surface detail – the process offers possibility to perform coining-like operations easily
- High accuracy caused by reduced springback – on impact with rigid tool high pressures will occur in short time period and residual elastic strains are minimized
- New assembling possibilities – parts can be joined by forming and by impact welding (without thermal affected zone)

The most widespread methods of high-velocity forming are explosive forming, electromagnetic forming and electrohydraulic forming.

In explosive forming pressure wave generated by high explosive presses sheet against die causing it to take the shape of the die. There are generally two types of explosive forming: contact process (the explosive charge is put directly to the surface of workpiece) and standoff process (the explosion takes place at a distance from blank; the pressure wave is transferred by water, or in some special cases, sand). The typical set-up for explosive forming is shown in Fig. 1.3. (ASM, 2006)

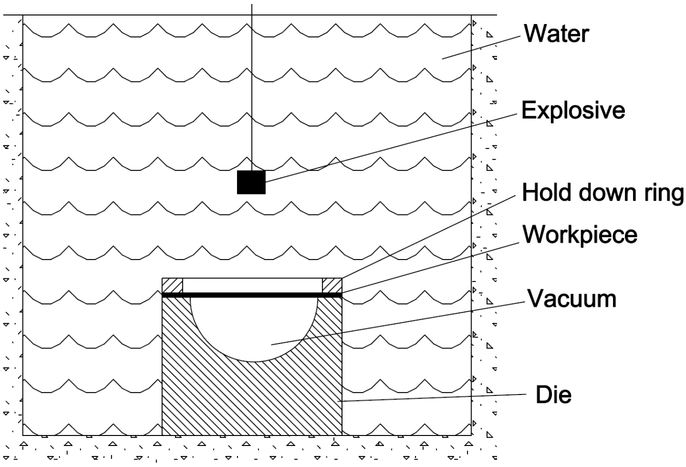


Fig. 1.3. Explosive forming process

In electromagnetic forming process large forces can be imparted to any electrically conductive workpiece by electromagnetic interaction. A significant amount of energy (up to 200 kJ) is stored in a large capacitor. The charge is switched over low-inductance conductive buswork through a coil. Large currents that run through the coil take the form of damped sine wave. This creates a strong transient magnetic field near the coil. The field induces eddy currents in conductive workpiece, which produces electromagnetic force between coil and the workpiece. The force can produce stresses in the workpiece that are several times larger than the material flow stress. This can cause plastic deformation of the workpiece and acceleration to velocities exceeding 100 m/s (ASM, 2006).

Electrohydraulic forming is a hybrid method between explosive and electromagnetic forming. In the process, an intense liquid-based shock wave is produced by an electrical current vaporizing a small volume of liquid in a spark gap of two electrodes. It is better controlled than explosive forming, but the forming energy is lower than in explosive forming (ASM, 2006).

The advantages are:

- Large and complex parts can be successfully formed
- Light and simple tools can be used, i.e. low-cost tooling
- Better formability is achieved in most applications
- Good accuracy due to low springback is achieved

The disadvantages are:

- Extra problems may emerge with handling of explosives (legal limitations, transportation, storing, utilization etc.)
- Not very widespread, information for successful implementation is hard to find

Stretch Forming

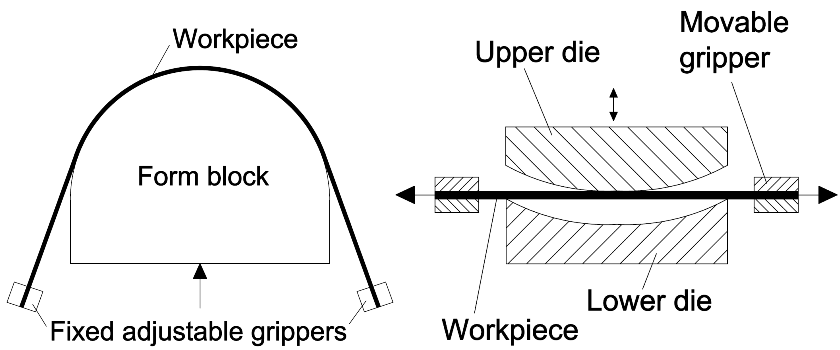
Stretching is a sheet forming process where blank is clamped around its edges and stretched over a die or form block. Unlike deep drawing, the sheet is gripped by a blank holder to prevent it from being drawn into the die. The ability of the sheet material to deform by elongation and uniform thinning are very important.

The stretch forming cannot produce parts with sharp contours. It is used mainly for making smooth large radius shapes (e.g. aircraft skin panels, automotive door and roof panels, etc.).

Several types of stretch forming exist. More frequently used types are as follows (ASM, 2006):

- Stretch draw forming
- Stretch wrapping, also known as rotary stretch forming
- Compression forming
- Radial draw forming

The most widespread type is stretch draw forming. In stretch draw forming process the sheet is stretched over a forming block (force is applied by moving grippers or by moving form block) (Fig. 1.4 a), or a die by a mating die of the desired shape (Fig. 1.4 b) while the workpiece is held in tension (it is extended slightly beyond the yield point to retain the desired shape).



(a) (b)

Fig. 1.4. Stretch forming process: (a) stretch draw forming with form block; (b) stretch draw forming with mating dies

Other types of stretch forming are combinations of stretching and bending operations.

In stretch forming process modular reconfigurable tool can be used as form block, similar to tools used in multi point forming, discussed in following paragraph. This makes the technology more flexible and suitable for low volume production.

The advantages are (ASM, 2006):

- Less force is needed (approx. 70%) than in conventional press forming
- Usually no buckles and wrinkles occur on the part
- Springback is relatively small
- Residual stresses are small
- Form blocks are made of inexpensive materials, e.g. wood, plastic, cast iron, low carbon steel
- Easy changeover to forming new parts

The disadvantages are (ASM, 2006):

- The limited ability to produce sharp contours and reentrant angles
- If the part is not pinched between mating dies, there is no opportunity to form out slight irregularities of the sheet blank
- Best results are achieved with rectangular blanks

Multi-point Forming

Multi-point forming (MPF) is described as a flexible type of die forming, where both dies are composed of several adjustable punches (Li, 1999; Li, 2002). The tips of the punches are spherical in order to produce as smooth contact with the workpiece as possible. The process is shown in Fig. 1.5. The principle of MPF is known for a couple of decades (Olsen, 1980), but the implementation of the process was delayed until development of technology made the control of the process feasible.

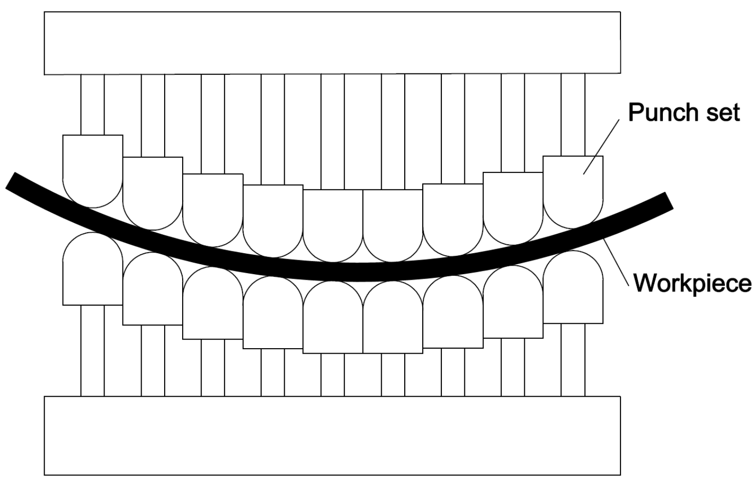


Fig. 1.5. Multipoint forming process

The main feature of multi-point forming is the ability to change the nature of the process by control of the height of punches during the process. There are three ways of punch adjustment (Li, 1999):

1. Relative fixation – the height of punches is adjusted before forming, relative height is not changing during the forming process
2. Passive adjustment – some punches (lower or upper punch set) are driven passively by the pressing force
3. Active adjustment – the position, speed and direction of the punches is dynamically changed during the forming process

Based on the adjustment described above, four practical methods of multi-point forming can be pointed out as follows (Li, 1999):

- Multi point die – punches of both dies are relatively fixed, the upper and lower tool (punch sets) are moved relatively like in conventional die forming.
- Multi-point half die – punches at one side are fixed before forming; at the other side passive adjustment is used (the punches of the tool apply some predefined reaction force to the workpiece).
- Multi-point press – punches at both sides are adjusted actively during the forming. At the start of the process, all punches are aligned. This is the most complex to control and the most promising method.
- Multi-point half press – punches are adjusted actively at one side and passively at the other side.

The control of the punches is very important, as dimpling and buckling may occur easily. Dimpling occurs due to local contact of punches. To avoid this, soft elastic sheets can be placed between workpiece and tools (Tan, 2007). Some researchers have proposed to substitute one die with elastic polyurethane pad, making the process more or less similar to rubber pad forming (Zhang, 2006).

For more accurate control of the deformation process, blank holder with adjustable holding forces can be added to the tool (Li, 2002; Sun, 2007). Multi-point forming allows easily to compensate for spring-back and to produce large parts with multiple sequential forming steps (there has to be some overlap by the tool between subsequent steps) (Li, 2002; Chen, 2005; Qian, 2007).

The advantages are:

- Large parts can be produced in smaller press using sequential forming
- No special tools are required
- High flexibility – reduced lead time and cost

The disadvantages are:

- The minimum size of features depends on punch size – shape with smaller details requires more complicated tools
- The process is much more complicated to control than conventional die forming

1.1.2 Complex-pass Techniques

The techniques meant by the term "complex-pass techniques" are those, where the final form of workpiece is achieved by complicated movement (trajectory) of the tool (or forming environment), or several subsequent forming passes are made.

Hand Hammering

Hand hammering is the oldest, and still used, metal forming technique in our modern manufacturing industry. In the forming process, a sheet is deformed with every hammer blow to the plastic state, which results in the local plastic deformations to cause the changes of the work piece shape. The process is very flexible, and allows to produce parts with complicated geometry using only few tools (Whittier, 1999).

In the process a sheet is hammered with tools, which geometry and material may largely vary. The sheet is supported by wooden base, sandbag or some other soft support (Whittier, 1999).

The process is time consuming and noisy. The quality is mainly influenced by the skills of the worker. Thus, accuracy of the form is different in case of different workers and from one part to other. This means that the process can be used mainly in repair works, production of single parts or prototypes and in production of art objects.

The advantages of the process are:

- The process is highly flexible
- No sophisticated and expensive tools are required

The disadvantages are:

- Problems with accuracy and repeatability are possible
- Accuracy depends on worker's skills
- Skilled worker is needed
- The process is time consuming

Wheeling

The machine used in this process is known as English wheel, wheeling machine and quick shaper. The machine has a frame shaped like a large, closed letter "C" (refer to Fig. 1.6). At the ends of the "C", there are two rollers. The roller on the top is called the rolling wheel, while the roller on the bottom is called the anvil wheel. The anvil wheel usually has a smaller diameter than the rolling wheel. The anvil wheel is convex in cross section, while the rolling wheel is cylindrical. The distance between the rollers is adjusted with the adjusting mechanism below the lower roller (Wheeling, 2007).

During the wheeling operation, a sheet of metal is repeatedly drawn between the rollers while the final thickness is set by the adjuster. The sheet movement between the forming rollers gradually deforms the sheet to obtain desired geometry. The choice of rollers and the trajectory of movement determine the final shape and finish of the part.

The wheeling machine does not require any external power; force applied by operator is enough. The process is quiet and clean.

As the process is manual, not numerically controlled, the achieving accuracy depends fully on skills of the operator. The surface finish of the parts produced using wheeling is smooth and good. Very complex shapes, such as automotive body panels, can be formed by wheeling. The process is used in production of prototype cars, motorcycles, boats and in aerospace industry. For many applications, working with an English wheel is easier than manual hammering of the sheet (English, 2007; Fournier, 2007; Powerhouse, 2007; Whittier, 1999).

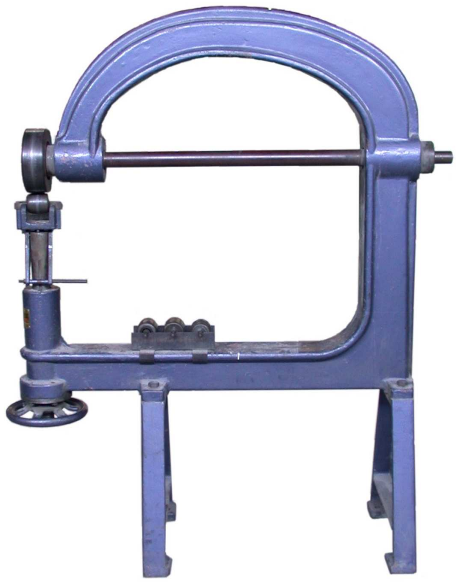


Fig. 1.6. English wheel (English, 2007)

The advantages are as follows:

- The wheeling machine is simple and low-cost
- Process is quiet
- Surface finish of parts is good

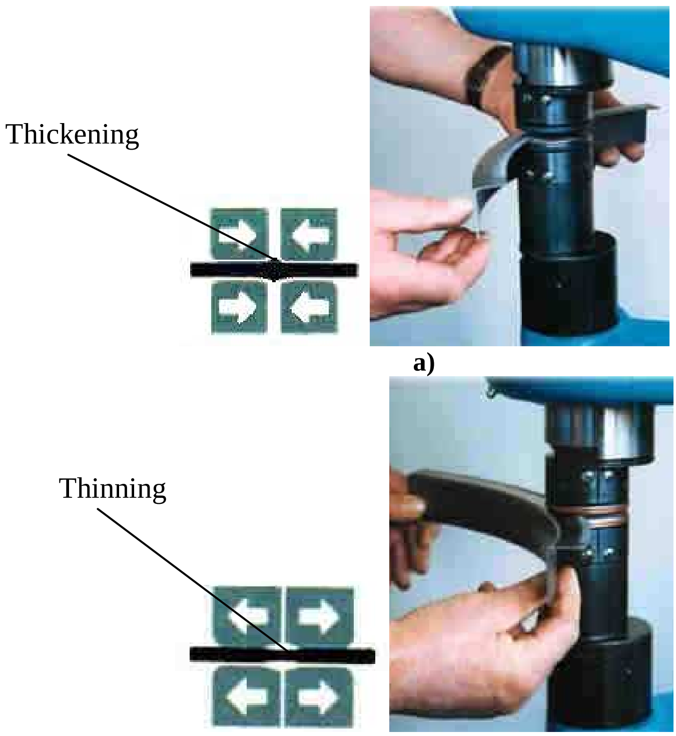
The disadvantages are as follows:

- Low accuracy
- Low productivity
- The accuracy depends on skills of the operator

Kraft Forming

The machines of Kraft forming are produced by Eckold GmbH & Co. The basic forming principle is shown in Fig. 1.7. The machine is able to perform several operations, including shrinking (Fig. 1.7 a), stretching (Fig. 1.7 b), flattening, doming, clinching, etc. The machine has upper and lower tool that are divided in two halves. The tools are able to grasp the sheet and stretch or shrink it between the two moving halves. The process includes many small forming steps, so relatively complex parts can be formed (Eckold-Clinchtechnik, 2007 a; Jadhav, 2004).

The machines are mechanically, pneumatically or hydraulically actuated. As the process is manually controlled, the accuracy depends fully on skills of the operator. The process has been used in production of high speed train parts, yachts and airplanes (Eckold-Clinchtechnik, 2007 a; Jadhav, 2004).



a)

b)

Fig. 1.7. Processes of Kraft forming: a) shrinking; b) stretching (Eckold-Clinchtechnik, 2007 b)

The main advantage of the process is:

- The process is flexible, many operations can be done using one machine tool

The disadvantages are:

- The process is manually controlled, it means low accuracy and repeatability
- The accuracy depends directly on skills of the operator
- Low productivity

Spinning

Spinning is a metal forming process where sheet is formed into seamless, axisymmetrical shapes by combination of rotational motion of a workpiece and force applied by a tool.

Some authors classify three types of spinning: manual spinning, power spinning and tube spinning (ASM, 2006; Boljanovic, 2004). In current thesis, power spinning is described separately in shear forming section, because several authors prefer to classify shear forming i.e. power spinning, separately (Wong, 2003); and as the mechanics is different, it seems to be reasonable.

The process is performed in spinning machine, similar to turning lathe. In the process a mandrel is fixed to the spindle of machine; sheet blank is pressed between mandrel and tailstock, and rotates with the spindle (Fig. 1.8). The forming is performed with a rigid tool or forming roller. The final shape of the part is obtained in several forming passes (stages). The process is performed usually in room temperature (ASM, 2006).

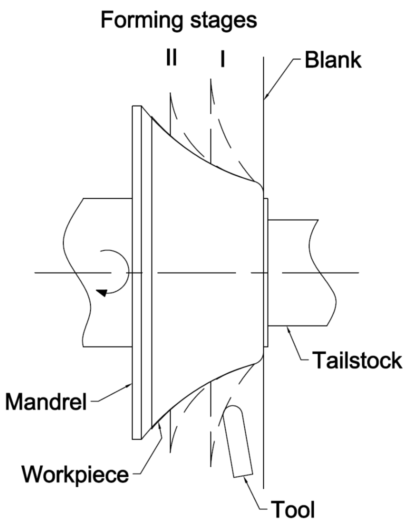


Fig. 1.8. Spinning process

Machines for producing large parts (blank size up to five meters in diameter) are produced. Aluminum sheet with thickness up to 6 mm and 3 mm in case of steel can be formed at room temperature (ASM, 2006).

Mandrel can be made of metal, wood or plastic by turning. The choice of material depends on desired quantity of parts.

The tool can be operated manually or by CNC (usually play-back systems) using servo-mechanical or servo-hydraulic actuators. Usually it is hard to program the forming process without play-back system; therefore skilled operator and manual spinning are used.

The process is mainly used in prototyping and for production runs of less than 1000 pieces, because of the low tooling costs (ASM, 2006).

Typical products made by using spinning are baskets, bowls, tanks, kettles, caps, pans, cups, cones, cylinders, drums, domes, etc.

The advantages are:

- Cost-effective for prototypes and small series
- Simple and inexpensive equipment

- The technique highly flexible

The disadvantages are:

- Only axisymmetrical parts can be produced
- Need for skilled worker

Shear Forming

This method is also known as power spinning and shear spinning. The process is performed in specialized shear forming machine, similar to turning lathe. Most modern shear forming machines have CNC (with play-back system). In the process a mandrel is fixed to the spindle of machine; sheet blank is pressed between mandrel and tailstock, and rotates with the spindle (Fig. 1.9). The forming is performed with a forming roller or several rollers. The final shape of the part is obtained in several forming passes (stages); the workpiece is annealed between the forming passes in order to increase the formability. The process is performed in room temperature or the workpiece is heated, depending on the material and thickness (ASM, 2006).

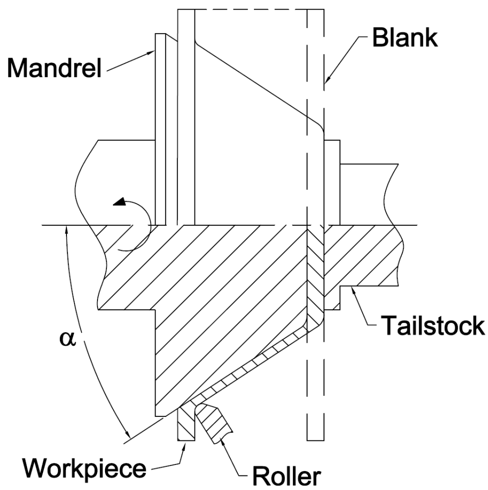


Fig. 1.9. Shear forming process

As the loading in shear forming is much higher than in manual spinning, the mandrel is made of cast iron or tool steel.

The process is economical for prototyping and small series production.

Large metal blanks (up to six meters in diameter) have been successfully formed using shear forming. Plate stock with thickness up to 25 mm can be formed at room temperature, and up to 140 mm at elevated temperature (ASM, 2006).

The shear forming is different from manual spinning in the fact, that the deformation takes place due to shear forces causing the thickness of the sheet to change (reduce). The final thickness of the sheet can be expressed by sine law as follows (ASM, 2006):

$$t = t_0 \sin \alpha , \qquad (1.1)$$

where t_0 is the thickness of the blank, t is the final thickness of the sheet after forming operation and α is half the apex angle of the cone.

As can be seen, if the desired geometry of the part is more complex than just a cone, the part will have variable thickness throughout the part in case of uniform thickness blank. However, it is possible to produce constant thickness part using a preformed blank with optimized geometry.

The applications of the process are similar to those of spinning, except shear forming allows to apply better automation, thus increasing productivity.

The advantages are:

- Large parts can be produced
- High flexibility is achieved

The disadvantages are:

- Only axisymmetrical parts can be produced
- Economical only for prototyping and small series production

CNC Hammering

The process is also known as roboshaping and incremental hammering or sometimes incremental forming. In the process sheet metal blank is fixed from its edges to a sheet holder, and is deformed with vibrating (hammering) numerically controlled tool (Fig. 1.10). The tool forms layer by layer in horizontal plane close to fixed edge. After each layer it descends a step downwards and forms next layer. As tool vibrates back and forth at high rate, the inertia holds workpiece in place and no specialized support is needed under the sheet. The tool is vibrating actuated by eccentric mechanism, electromagnetic or pneumatic system. The rate of vibration of the tool is 100 Hz or more, and the amplitude is more than 1 mm (Schafer, 2005).

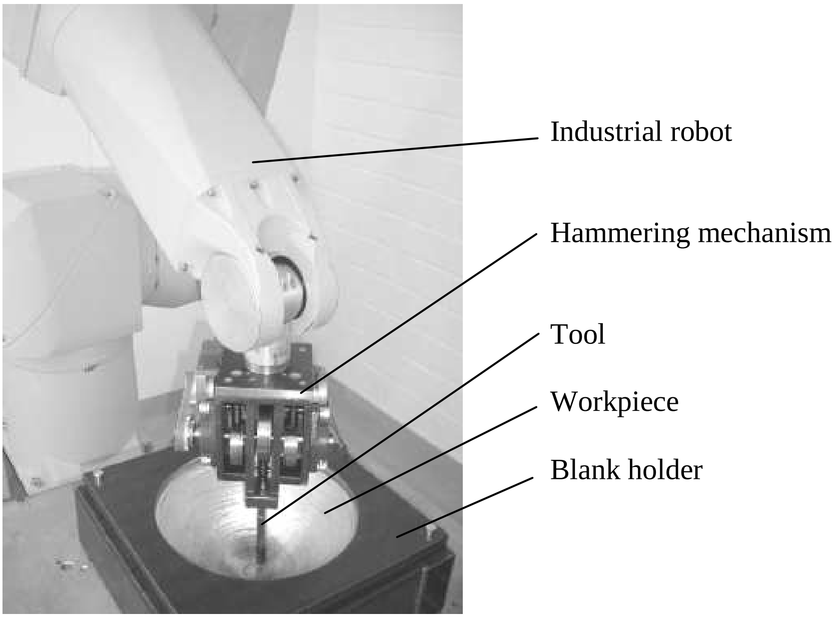


Fig. 1.10. Roboshaping process (Schafer, 2005)

The geometry of the tool is simple – cylinder with spherical tip. The tool is moved along using robot or some sort of special CNC actuator.

The quality of the part depends directly on toolpaths and hammering rate of the tool (Mori, 1996). The dimensions of the parts are limited by capabilities of the robot used in the process, so parts with dimensions in meters can be made. On the other hand, the same hammering principle can be used for forming small objects. Saotome & Okomoto described a microforming system, where a part with 600 μm edge length and 10 μm thickness was produced (Saotome, 2001).

The advantages are:

- No special tooling is required
- High flexibility is achieved
- Large parts can be produced
- Highly complex optimized forming toolpaths can be realized using CAD/CAM systems

The disadvantages are:

- The process is noisy
- Surface roughness is not acceptable for many applications
- Preparing toolpaths can be very complicated

Peen Forming

The process is also known as shot peen forming and bullet jet forming. Shot peen forming is a dieless sheet forming process that is performed at room temperature, where small spherical steel shots impact the surface of the work piece. Every shot acts as a small hammer, producing local plastic deformation that causes residual compressive stress and stretching of the upper surface. The combination of elastic stretching and compressive stress generation causes the material to develop a convex curvature on the peened side. If the shot velocity is increased, then at some point the whole cross-section of the sheet is deformed plastically causing concave form of the surface. The nature of the surface (concave or convex) produced depends mainly on the sheet (thickness, mechanical properties, etc), diameter of the particles and shot velocity (ASM, 2006; Metal, 2007).

The shot peen forming process is suitable for forming large panel-type parts where the bend radii are large and without abrupt changes in contour. Although no dies are required for peen forming, for severe forming applications, some fixtures are sometimes used. Because it is a dieless process, the costs of development and the time spent for manufacturing of hard dies are absent. The process itself is time consuming, and is effective if batch size is small.

Parts formed by peen forming exhibit increased resistance to flexural bending fatigue (Metal, 2007).

Nowadays, peen forming facilities can be distinguished by the way the shot medium is accelerated. The most wide-spread types are as follows:

- Centrifugal wheel spinning systems
- Air pressure systems
- Injector peening systems
- Injector-gravitation peening systems

The most suitable material for shots is round steel balls, e.g. bearing balls (100Cr6, hardness 57 to 60 HRC). Ball diameter is usually 2 to 4 mm, or in some cases up to 10 mm. (ASM, 2006)

Shot peen forming is typically used in aerospace and shipbuilding industry.

The advantages are:

- Increased fatigue strength
- Large parts can be manufactured flexibly

The disadvantages are:

- The quality of the parts depends on many parameters, that have to be controlled on-line – control of the process is complicated
- Parts with only large radiuses of curvature can be formed
- The inferior surface quality may be a problem

Thermal Forming

Thermal forming of sheet metal is a process where permanent deformation of sheet is caused by local thermal treatment without application of external mechanical forces. It is based on thermal expansion of materials. If the expansion is limited in two dimensions, compressive stresses build up and result in localized plastic deformation (if the temperature is high enough). The plastic deformation occurs in the third dimension. The plastically deformed material does not return to its original place after cooling, causing permanent change in shape of whole component. No melting is allowed to take place in the forming process.

The process relies on localized controllable heating source. Four energy sources have been used in thermal forming: a gas flame, an electric induction coil, a plasma torch and a laser beam.

In forming with gas flame usually handheld oxyacetylene torch is used. This is the oldest, least controllable and reproducible technique. The equipment is inexpensive, but operator has to be very skilled and experienced. Today, the technique is used mainly in straightening tasks of structures (especially after welding operations), and in bending of plates for ship construction.

Heating with high-frequency electric induction coil is the most efficient method, because the heat is generated directly in the metal by induced eddy current. The higher the frequency used, the shallower the depth of heating, i.e. the process is well controllable compared to other heating methods.

Lasers provide a beam of visible light with significant intensity of energy. It may be used to quickly heating up materials with well controlled manner. A part of energy from laser beam is reflected away, the other is absorbed into material (only less than 10%). To increase the amount of absorbed energy, graphite spray coating of the workpiece is used (ASM, 2006).

Plasma arc systems are usually less expensive and safer to use than high-power laser systems. The overall energy transfer ratio is generally > 85% (ASM, 2006).

In the thermal forming system with plasma arc, one heating source and two cooling streams are usually present. For cooling CO_2 gas is usually used. One cooling jet is at the opposite side of sheet, directly under the heating source. The other cooling jet is on the same side of the sheet as heating source, it moves at certain distance behind the heating source, following the same toolpath. By varying the heating and cooling intensity, and the second cooling jet's distance from the heater, it is possible to make sheet bending toward and away from the heating source (ASM, 2006).

In effective automatic thermal forming system heat source and cooling jets are moved by robot manipulators. The toolpaths are prepared using specialized CAM software.

The advantages of thermal forming are:

- High flexibility – no special tooling is required
- Large parts can be produced

The disadvantages are:

- The control of the process is very complex
- The process is very sensitive to process parameters
- Heating of the sheet metal may influence the properties of the sheet
- Insufficient information about the successful implementation of the process is available, as the process is still in research stage

1.1.3 Incremental Sheet Forming

Process Description

Incremental sheet forming (ISF) is a novel technology for sheet metal forming. ISF is a flexible process – the set-up of production of the new part is a matter of hours rather than days, like in some traditional forming methods. The parts of complicated shape can be formed by use of a computer numerically controlled (CNC) device. The process uses accurate CAD data that represents the part produced. No considerable manual work is required, and thus the repeatability of the process is very good. The drawback of the process is relatively long forming time. For that reason, ISF is feasible in prototype and small series production. Incremental forming technique has been developed during the last decade (see (Kim, 2000), (Iseki, 2001) and (Shim, 2001)).

The process of ISF is based on layered manufacturing principles, where the model is divided into horizontal slices. The numerically controlled (NC) toolpath is prepared using contours of these slices. In the process, simple spherical forming tool is moved along NC controlled toolpath as follows (see Fig. 1.11): tool moves downwards, contacts the sheet, then draws a contour on the horizontal plane, and then makes a step downwards, draws next contour, and so forth until operation is completed. The process can be performed on universal 3 or more axis CNC milling machine or with industrial robot. For preparation of NC –code general purpose Computer Automated Manufacturing (CAM) software can be used.

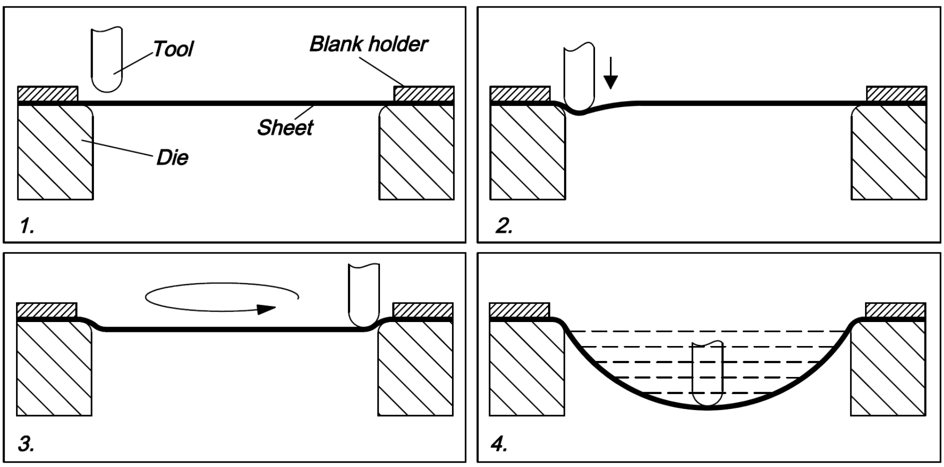
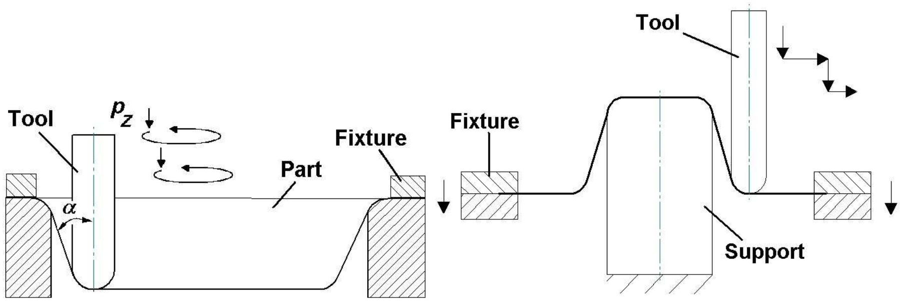


Fig. 1.11. Schematic diagram of the incremental sheet metal forming process (Kim, 2000)

The edges of the sheet blank remain usually fixed in horizontal plane by special blank holder throughout the operation.

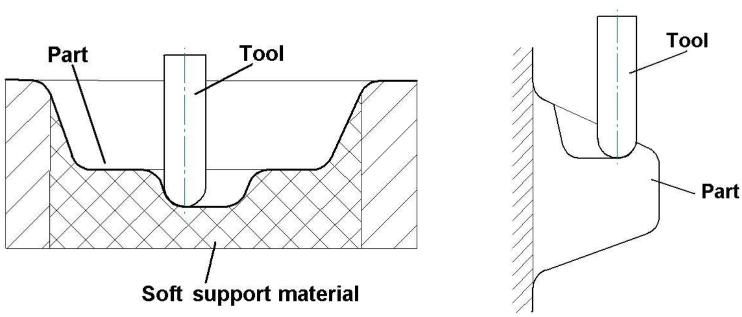
There are two basic approaches of incremental forming process: forming without support (Fig. 1.12 a) and forming with support (Fig 1.12 b), also known as negative and positive forming, respectively. Generally, the positive forming allows achieving better results but is more complex.



(a) (b)

Fig. 1.12. Two fundamental types of ISF

In Fig. 1.13, there are two additional approaches studied by the authors, but they are not under the focus of the current thesis. In Fig. 1.13 (a) soft support material is used to achieve better form accuracy. Support material should be sufficiently plastic to be able to flow away under the tool, but on the other hand, it should be rigid enough to support the sheet blank. The material could be clay, tar, modeling paste, etc. The authors used in their study modeling paste. Fig. 1.13 (b) shows set-up for forming areas of the part not possible or hard to form in previous steps. This can be accomplished better with 5-axis machining centre or by using industrial robot.



(a) (b)

Fig. 1.13. Different incremental forming processes

New trend in ISF is to use industrial robots for moving the forming tool (Lamminen, 2005) or using two robots – one for moving the forming tool, the second, for moving the support (Meier, 2005; Meier, 2007).

As a result of using the ISF process, sheet metal parts with complicated geometry can be manufactured with simple and relatively inexpensive tool. As expensive and highly dedicated tools are not needed, incremental forming is especially suitable for production of prototypes and for small series production.

Some authors prefer to use the term Single Point Forming for negative ISF and Two Point Forming for positive ISF (Jeswiet, 2005 b). The idea is, that in the first case only the tool is in contact with the sheet. In the second case, the support is also in contact with the sheet.

The only commercial producer of ISF machines is AMINO Inc. from Japan (Amino, 2007). The company produces machines that are specialized for positive forming, i.e. there is vertically movable sheet holder. The machines have stiff solid structure; feeds are high (up to 30 m/min). The largest machine tool is able to process sheet with dimensions up to 2100x1450 mm. The company is producing also equipment for fluid cell forming of sheet metal. The company is planning to produce machines that combine stretch forming and incremental forming principles (Maki, 2006).

Literature Overview

An approximate deformation analysis for the incremental bulging of sheet metal using a ball has been developed by Iseki (Iseki, 2001). The incremental bulging method has been applied for non-symmetric shallow shells. In the study the plane-strain deformation model has been proposed (Iseki, 2001). This model makes an approximation that the sheet metal in contact with the ball stretches uniformly. The friction at the interface between tool and sheet, the plane anisotropy and Bausinger effects of the sheet material are neglected. The closed form expressions for the uniform strains ε_x and ε_t of the deformed shell are pointed out. The tensile force is determined from the condition that the un-deformed part is rigidly moved by the stiffness of the shell. The results, obtained by the approximate deformation analysis, FEM analysis and experiments are in good agreement. However, the complete incremental bulging operation has been not modeled in the study (Iseki, 2001).

Vertical wall surface forming of rectangular shell using multistage incremental forming was studied by Iseki (Iseki, 2002). A method of calculating for the approximate distribution of thickness strain and the maximum bulging height has been proposed using a plane-strain deformation model with a constant strain gradient. Dai et al. obtained a mapping relationship between the blank and its formed specimen under the condition of even strain (Dai, 2000). A simplified calculation model was developed by Kim & Yang, assuming that all deformation occurs only by shear deformation (Kim, 2000). The intermediate shape was determined from the predicted thickness strain in order to distribute the deformation uniformly. Next, the sheet metal was deformed by a double-pass forming undergoing the calculated intermediate shape. The proposed method was applied to the analysis of an ellipsoidal cup and a clover cup.

The formability in incremental forming of sheet metal was studied in several papers (Kim, 2000; Shim, 2001; Filice, 2002; Kim, 2002; Kim, 2003; Park, 2003; Fratini, 2004; Ambrogio, 2005; Jeswiet, 2005 a; Meyer, 2005; Ham, 2007; Hussain, 2007). Shim & Park made a study where a forming tool containing a freely rotating ball was developed (Shim, 2001). The results observed in the tests were examined by grid measurement and finite element analysis. A unique forming limit curve was obtained. It was pointed out that the forming limit curve is quite different from that in conventional forming. It appears to be a straight line with a negative slope in the positive region of the minor strain in the forming limit diagram. It was also observed that the cracks occur mostly at the corners (due to greater deformation at the corners). Kim & Park studied the effects of process parameters (tool size, feed rate, plane-anisotropy) on formability (Kim, 2002). The formability of an aluminum sheet under various forming conditions was considered in the next study of the same authors (Kim, 2003). Complex shapes (octagonal cones, stepped shape, bucket shape) were produced with the proposed technique. In another formability study, the strain values as large as 300% (material soft aluminum), achieved by ISF, were reported (Jeswiet, 2005 a). Hussain et al. investigated the maximum forming angle in negative ISF, and concluded that the maximum angle depends on the shape of the part (Hussain, 2007).

Since low accuracy is a serious problem in ISF, several studies are devoted to this. Hirt et al. investigated the causes of low accuracy and developed an error compensation system, which uses CMM and a special geometry correction algorithm (Hirt, 2004). Ambrogio et al. dealt with the compensation of elastic springback (Ambrogio, 2004). In another study empirical model was used to estimate and compensate for geometry errors (Ambrogio, 2007). Micari et al. discussed different approaches for improving accuracy, including use of flexible support, counter pressure, multipoint tools, backdrawing incremental forming with 4-axis machine tool, etc. (Micari, 2007).

Numerical modeling using FEA has been performed in many studies (Shim, 2001; Filice, 2002; Kim, 2002; Park, 2003; Ambrogio, 2004; Ceretti, 2004; Hirt, 2004; Ambrogio, 2005; Bambach, 2005; Giardini, 2005; He, 2005; Henrard, 2005; Mao, 2006; Capece, 2007). Most of the studies focus on formability and prediction of thinning. Both types of FEA codes, explicit and implicit, have been used by different authors. In majority of studies, the sheet is modeled using 3D shell elements. All studies indicate that the simulation of the ISF is very time consuming and complicated. Bambach et al. presented new validation procedure for FEA (Bambach, 2005). The maximum strain deviation of the analysis was 14%. Some studies deal with the possibilities of simplification of the analysis (He, 2005; Henrard, 2005). In the simulations solid elements were used. To speed-up calculation, the axisymmetrical component was modeled partially. Two different FEA codes were compared.

In their study, Shim & Park and Kim & Park (Shim, 2001; Kim, 2002) used a commercial FEA code, PAM-STAMP, for the analysis of sheet metal incremental forming. It was used to analyze the deformation that occurred in the straight groove test. The results of this analysis provided enough information to understand the trend of deformation.

In some papers, detailed experimental studies, based on the design of experiments theory, were described (Ham, 2006; Ambrogio, 2007; Duflou, 2007 a; Ham, 2007). Ambrogio et al. presented experimental models for predicting form deviations (Ambrogio, 2007). Some papers focus on the influence of product and process parameters on formability (maximum forming angle) (Ham, 2006 and Ham, 2007). Duflou et al. studied the influence of some parameters on forming forces (Duflou, 2007 a).

Different die technologies and dieless technologies for trial and small lot production were compared by Naganawa (Naganawa, 2000). The principles and features of the recently developed sheet forming processes were overviewed by Strano (Strano, 2003). A special attention was paid to ISF, cone spinning and flow-forming.

Jeswiet et al. made a case study of forming parts of solar cooker (Jeswiet, 2005 c). They observed problems due to springback and formability even with soft aluminum.

Several studies focus on forming forces (Duflou, 2005; Jeswiet, 2005 b; Filice, 2006; Duflou, 2007 a). It was observed that the force vector sum in ISF is decreasing considerably before the material failure. This can be used as material failure indicator in systems with on-line monitoring in order to take preventive action (Duflou, 2005; Filice, 2006).

Some papers describe ISF with industrial robot. Lamminen et al. studied formability in negative and positive ISF (Lamminen, 2004; Lamminen, 2005). Meier et al. used two robots to form sheet metal (Meier, 2005; Meier, 2007). One robot moved the tool, and the other one was used to move the support. This approach makes the ISF technology much more flexible.

A study was made by Duflou et al., where the forming process was accomplished with industrial robot and, in addition, local heating of the sheet with a laser was used (Duflou, 2007 b). The laser beam was heating the sheet at the opposite side of the tool while forming (the laser spot was moved in synchronous manner with the tool) in order to make the material to behave more plastically. This resulted in decreasing forming forces up to 50%, enhanced accuracy and formability.

In a paper written by Allwood et al., the design of special ISF machine tool with on-line measuring of forming forces is described (Allwood, 2005).

Some new approaches of using ISF can be found in literature. Teramae et al. used incremental forming process for producing tube flanges (Teramae, 2007). Another paper describes a study concerning incremental forming of thin walls in combination with machining processes of parts for aerospace industry (Smith, 2007). With this approach, more complicated components can be produced more cost effectively.

Limitations of the Process

Incremental forming has several limitations. First, with incremental forming it is hard to produce parts that have steep walls. Because of the principle of the forming, all deformations occur prevalently by shear deformation (Kim, 2000), so for calculation of thickness the same equation can be used as in shear forming (see equation 1.1) (ASM, 1988). The equation is known as Sine Law.

The decrease of wall thickness is the most serious limitation of the process.

The second limitation is the low accuracy which is caused by springback. High accuracy is hard to achieve unless some sort of compensation procedure is used. It appears to be problematic mainly in forming of elastic materials, e.g. stainless steel. The third limitation is processing time. If high surface quality has to be achieved, then small vertical step size is needed. It causes process to be very time consuming.

1.2 Objectives and Tasks

1.2.1 Objectives

The objective of the doctoral thesis is to develop methods and techniques for design of products and processes for ISF technology of flexible manufacturing of sheet metal prototypes and small series products.

1.2.2 Tasks

The achieving of the objective, described above, requires solving some tasks. The tasks are as follows:

- Overview of different flexible sheet metal forming processes
- The study of mechanics of the process (numerical and theoretical study)
- Experimental study – the investigation of the influence of product and process parameters to the quality of products
- The techniques for design of products and processes based on created models
- The improvement of Incremental Sheet Forming (better accuracy and process optimization)

1.2.3 Scientific Novelty

ISF is a novel technology developed during last decade. There are more questions than answers in this area. Both, theoretical and experimental study concerning ISF process modeling, limitation analysis, technological aspects, etc. are still in development.

The most important novelties of the current thesis are as follows:

- In the current study FEA based numerical procedure is proposed for estimating forming forces in ISF process
- The theoretical model for describing forming force in ISF process has been improved by introducing the influence of plastic anisotropy
- Experimental models for estimating influence of wall angle, vertical step size, tool radius and stretching force on important quality indicators (step down line parameters, form and flatness deviations, forming forces, etc.) have been built

1.2.4 Limits of the Study

The thesis gives overview of sheet metal forming processes that can be used for building prototypes. The main emphasis is on incremental sheet forming processes. The thesis includes literature overview, some theoretical aspects and numerical analysis using finite element method. More detailed part of the thesis is experimental study, where forming with and without support has been investigated. The influence of the most important parameters on some quality indicators is studied. An important part of the thesis deals with problems concerning implementation of the forming technology. Some recommendations are given and case studies of successful applications are shown.

Due to time and economical constraints, the study is limited to only few aspects of incremental sheet forming technology. The aspects associated with materials, tribology, design of new machine tools, quality testing, automation, etc. are not covered in the current thesis. However, these topics are not considered as less important.

2 THEORETICAL AND NUMERICAL ANALYSIS

ISF process is relatively new, and many aspects of the process are still not investigated. In the current chapter theoretical models concerning forming forces and formability, and also numerical analysis, are considered. Forming forces and formability are issues that have big practical importance.

2.1 Theoretical Models

2.1.1 Forming Forces

A simplified theoretical model for estimating force components in ISF process is proposed by Iseki (Iseki, 2001). In the following part, the latter model is extended in order to consider the plastic anisotropy.

For taking account plastic anisotropy, the classical von Mises yield criteria should be replaced. In the current thesis the normal anisotropy is assumed. The Hill's second and higher order yield criteria are employed for describing anisotropy. The approximation for the forming load components F_x and F_z is given in (Iseki, 2001) as

$$F_x = F_t(1-\cos(\theta)),$$
$$F_z = F_t \sin(\theta), \qquad (2.1)$$

where F_t and θ stand for the tensile force and contact angle, respectively. The contact angle θ is determined by the geometrical relations omitted here for conciseness sake (see details in (Iseki, 2001)). The geometrical interpretation of the contact angle θ is represented in Fig. 1.12, where

$$\alpha = 90^o - \theta. \qquad (2.2)$$

Let us concentrate on evaluation of the tensile force F_t, since it depends on material properties including plastic anisotropy. Uniform stretching of the sheet metal under plane-strain condition is assumed. The bending stress and the friction force are neglected. The tensile force is computed approximately as

$$F_t = A\sigma_x = 2R\,t\sigma_x. \qquad (2.3)$$

In (2.3) the cross section area of the deformed strip, the stress component on the x-axis, the radius of the tool and the sheet thickness are denoted by A, σ_x, R and t, respectively. It is assumed that the stress component in thickness direction σ_t and the strain component ε_y are negligible (y axis is perpendicular to tool moving direction).

From material incompressibility it yields that $\varepsilon_t = -\varepsilon_x$. The Hill's non-quadratic yield criterion can be expressed in the case of plane strain condition and normal anisotropy (Hill, 1979) as

$$\bar{\sigma} = \left(\frac{1}{2(1+R_a)} \left| \sigma_x + \sigma_y \right|^m + \frac{(1+2R_a)}{2(1+R_a)} \left| \sigma_x - \sigma_y \right|^m \right)^{\frac{1}{m}}. \qquad (2.4)$$

In (2.4) σ_x, σ_z and $\bar{\sigma}$ stand for the stress components and equivalent stress, respectively; R_a is an anisotropy parameter defined as width to thickness strain increment ratio

$$R_a = \frac{\varepsilon_w}{\varepsilon_t}. \qquad (2.5)$$

The exponent m ($m > 0$) in (2.4) depends on the normal anisotropy coefficient R_a

$$\left(\frac{\sigma_b}{\bar{\sigma}} \right)^m = \frac{(1+R_a)}{2^{m-1}}, \qquad (2.6)$$

where σ_b denotes the yield stress in equi-biaxial tension. In the case $m = 2$, the criterion (2.4) reduces to the Hill's second order criterion (Hill, 1952).

The ratio between equivalent stress $\bar{\sigma}$ and the stress component σ_x can be expressed as (see (2.4))

$$\frac{\bar{\sigma}}{\sigma_x} = \left(\frac{(1+\gamma)^m}{2(1+R_a)} + \frac{(1+2R_a)(1-\gamma)^m}{2(1+R_a)} \right)^{\frac{1}{m}}, \qquad (2.7)$$

where $\gamma = \sigma_y / \sigma_x$.

From the normality rule, yield criterion (2.4) and assumption that ε_y is negligible, it implies that

$$\frac{\partial \bar{\sigma}}{\partial \sigma_z} = 0. \qquad (2.8).$$

Applying the relation (2.8) to the equivalent stress given by (2.7) yields

$$\left(\frac{(1+\gamma)^m}{2(1+R_a)} + \frac{(1+2R_a)(1-\gamma)^m}{2(1+R_a)} \right)^{\left(\frac{1}{m}-1\right)} \frac{1}{2(1+R_a)} \left[(1+\gamma)^{m-1} - (1+2R_a)(1-\gamma)^{m-1} \right] = 0. \qquad (2.9)$$

Solving the algebraic equation (2.9) with respect to γ, one obtains (it is assumed that $\bar{\sigma} > 0$)

$$\gamma = \frac{\sigma_y}{\sigma_x} = \frac{(1+2R_a)^{\frac{1}{m-1}} - 1}{(1+2R_a)^{\frac{1}{m-1}} + 1}. \qquad (2.10)$$

Substituting (2.10) in (2.7) yields

$$\frac{\overline{\sigma}}{\sigma_x} = \left(\frac{(1+2R_a)}{(1+R_a)} \right)^{\frac{1}{m}} \left(\frac{2}{(1+2R_a)^{\frac{1}{m-1}}+1} \right)^{\frac{m-1}{m}} . \qquad (2.11)$$

Using (2.11) the tensile force F_t, given by (2.3), can be rewritten in terms of equivalent stress as

$$F_t = 2Rt\overline{\sigma} \left(\frac{(1+R_a)}{(1+2R_a)} \right)^{\frac{1}{m}} \left(\frac{(1+2R_a)^{\frac{1}{m-1}}+1}{2} \right)^{\frac{m-1}{m}} . \qquad (2.12)$$

The equivalent strain increment corresponding to yield criterion (2.4) can be expressed as follows (Hill, 1979):

$$\overline{\varepsilon} = \frac{[2(1+R_a)]^{\frac{1}{m}}}{2} \left[\left| \varepsilon_x + \varepsilon_y \right|^{\frac{m}{m-1}} + \left(\frac{\left| \varepsilon_x - \varepsilon_y \right|^m}{1+2R_a} \right)^{\frac{1}{m-1}} \right]^{\frac{m-1}{m}} . \qquad (2.13)$$

Due to $\varepsilon_y = 0$ (ε_y is assumed to be negligible), the relation (2.13) reduces to

$$\overline{\varepsilon} = \frac{[2(1+R_a)]^{\frac{1}{m}}}{2} \left[1 + \frac{1}{(1+2R_a)^{\frac{1}{m-1}}} \right]^{\frac{m-1}{m}} \varepsilon_x . \qquad (2.14)$$

The isotropic (work) hardening of the material is considered. The evolution of the yield surface is described with the equivalent plastic strain $\overline{\varepsilon}$ and strain hardening parameters. The stress-strain curve can be fitted by a power hardening law of the form

$$\overline{\sigma} = K\overline{\varepsilon}^n . \qquad (2.15)$$

In (2.15) K and n stand for the strength coefficient and strain hardening exponent, respectively. These material parameters can be determined experimentally from standard tensile tests. Inserting (2.15), (2.13) and the thickness relation

$$t = t_0 e^{-\varepsilon_x} \qquad (2.16)$$

in (2.12), one obtains the tensile force F_t in terms of material parameters and ε_x as

$$F_t = 2RK\left\{\frac{[2(1+R_a)]^{\frac{1}{m}}}{2}\left[1+\frac{1}{(1+2R_a)^{\frac{1}{m-1}}}\right]^{\frac{m-1}{m}}\right\}^n \times$$

$$\left(\frac{(1+R_a)}{(1+2R_a)}\right)^{\frac{1}{m}}\left(\frac{(1+2R_a)^{\frac{1}{m-1}}+1}{2}\right)^{\frac{m-1}{m}} t_0 e^{-\varepsilon_x}\varepsilon_x{}^n \qquad (2.17)$$

The strain component ε_x is determined by forming geometry. The closed form formulas for computing ε_x are given in (Iseki, 2001). In the case of quadratic Hill's yield criteria $m = 2$ and the expression of the tensile force can be given in considerably simpler form as

$$F_t = 2RK\left(\frac{(1+R_a)}{\sqrt{1+2R_a}}\right)^{n+1} t_0 e^{-\varepsilon_x}\varepsilon_x{}^n . \qquad (2.18)$$

The forming load components can be evaluated by substituting the expression of the tensile force (2.18) or (2.17) in (2.1).

The forming load components in F_z (vertical direction) and F_x (tool moving direction) are depicted in Fig. 2.1. The forming load components obtained from theoretical analysis, are given as functions of the bulging height (forming geometry), but the corresponding experimental (and numerical) results describe dependence on forming time. Thus, unique comparison of these results is complicated. The equipment used in experimental study allows determining forming time dependences only. However, the magnitudes of the forming load and its components, the ratio F_z / F_x, corresponding to theoretical and experimental (and numerical) models are found to be close.

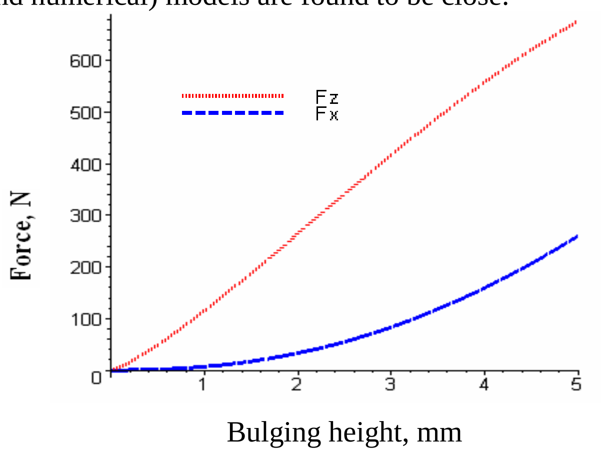


Fig. 2.1. Forming force components (Pohlak, 2006 b)

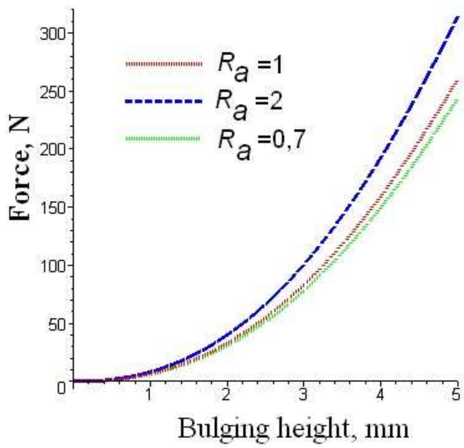


Fig. 2.2. Influence of the plastic anisotropy on the forming load F_x (Pohlak, 2006 b)

In Fig. 2.2 the forming load components F_x, corresponding to different values of the plastic anisotropy parameter R_a, are plotted. In the case of $R_a = 1$ (isotropic material), the results obtained by use of theoretical model proposed in the current study and Iseki's models coincide.

It is seen from Fig. 2.2, that the influence of the plastic anisotropy on material formability is significant. As it can be expected, the forming load component F_x increases with increasing value of the anisotropy parameter R_a (see Fig. 2.2).

In order to fit the experimental results more precisely, an advanced yield criteria BBC2003 (Banabic, 2005) are introduced for modeling plastic anisotropy. Unfortunately, higher accuracy achieved by applying advanced yield criteria is accompanied by increasing number of mechanical tests (uniaxial and equi-biaxial tensile tests). Besides, nonlinear system of algebraic equations is necessary to solve for computing the anisotropy coefficients. Material parameters identification problem in the case of yield criteria BBC2003 is studied by the author of the current thesis and co-workers in (Majak, 2007 a; Majak 2007 b).

2.1.2 Formability

It is well-known that the forming limit curve is quite different in the case of ISF from that in conventional forming (see (Kim, 2002) and (Kim, 2003)). It appears to be a straight line with a negative slope in the positive region of the minor strain on the forming limit diagram. According to this, FLD created for traditional forming processes cannot be used effectively for ISF process analysis. However, no standard test procedure has been defined for determining the forming limit curve in ISF process. Both, experimental and theoretical studies in this area are in development stage. Some general considerations for test design are proposed in (Iseki, 2001) and (Filice, 2002). In (Filice, 2002), tool paths, corresponding to uni-axial and bi-axial stretching conditions, are given. In (Iseki, 2001), the empirical formula is used for FLD approximation.

The FLD is used as the tool for estimation material formability in ISF process. The forming strategies are developed in order to cover the entire deformation mode corresponding to the positive minor strain region of the FLD.

Generally, in ISF higher strains can be achieved, in some cases much higher – Jeswiet et al. reported strains over 300% (Al 3003-O) (Jeswiet, 2005 a). Although, the formability is higher in ISF (forming limit curve is higher), more geometrical limitations appear when compared with traditional forming technologies, like deep drawing. This is caused by different process mechanics – in deep drawing material is pulled into the die, while in ISF the deformation is local, and material will not be pulled into processing area. Thus, literally, height of the part features is built at the cost of part thickness.

In order to create the FLD, the circular grid path with 3 mm diameter was printed on the sheet surface and ISF process was performed up to failure. Two kinds of toolpaths were used: helical and linear (back and forth ramp). The limit strains were determined from the circular grid near necks and fractures (Fig. 2.3).

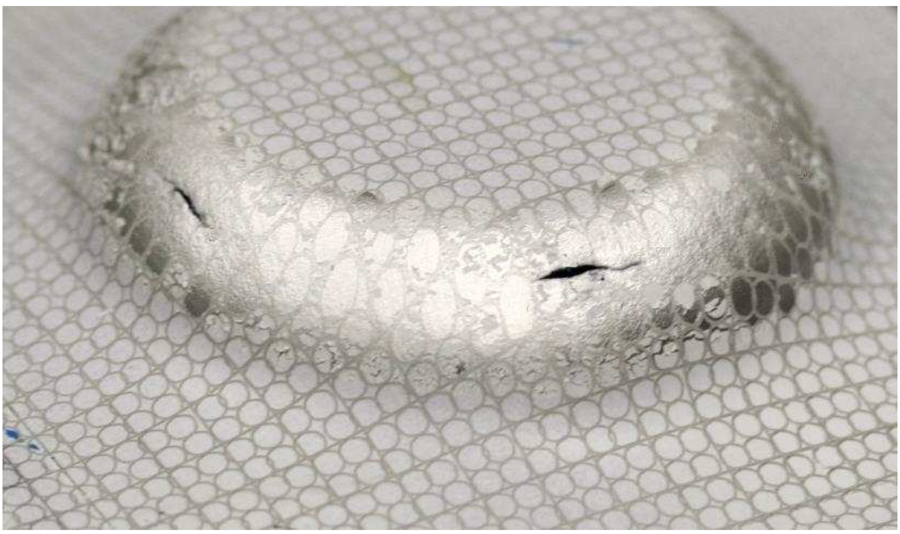


Fig. 2.3. Incremental formability test (Pohlak, 2007 b)

The obtained experimental results are fitted by straight line in FLD. Deviations of the experimental limit strains from obtained linear approximation appears not significant (see Fig. 2.4).

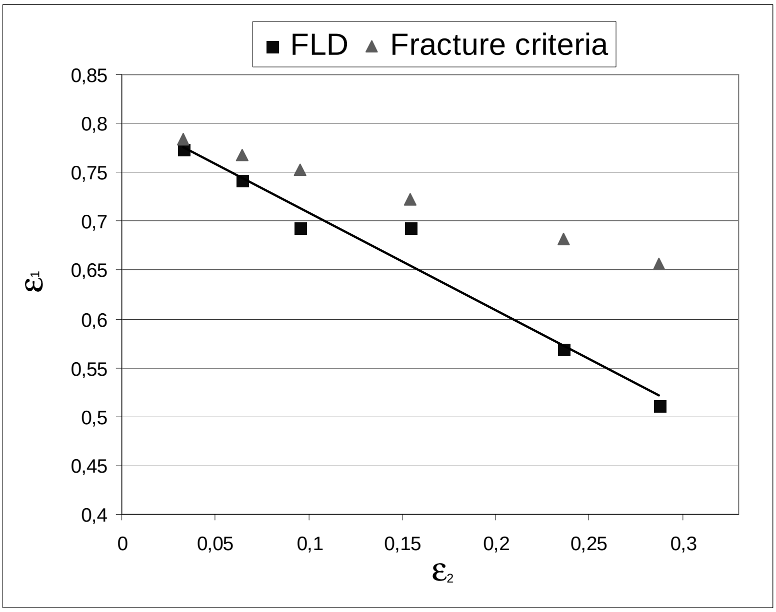


Fig. 2.4 Forming Limit Diagram for ISF process (Pohlak, 2006 a)

Theoretical fracture strains are determined using the normalized Cockcroft-Latham criterion (Urban, 2003):

$$\int_0^{\bar{\varepsilon}^{fr}} \frac{\sigma_1}{\bar{\sigma}} d\bar{\varepsilon} = C . \tag{2.19}$$

In (2.19) σ_1 is the maximal principal stress, $\bar{\sigma}$ and $\bar{\varepsilon}$ are equivalent stress and strain, respectively. Equivalent fracture strain is denoted by $\bar{\varepsilon}^{fr}$. The calculated fracture strain and experimental limit strain corresponding to the plane strain condition, are found to be close (Fig. 2.4). This result is in accordance with the empirical formula

$$\varepsilon_1 + \varepsilon_2 = \varepsilon^{fr} \tag{2.20}$$

proposed in (Pohlak, 2005). In (2.20) ε_1 and ε_2 stand for major and minor principal strains, respectively.

Based on the results, obtained above, we can conclude the following:

- it is reasonable to use general linear approach for limit strains

  $$\varepsilon_1 + c_1\varepsilon_2 = c_2 , \tag{2.21}$$

  where c_1 and c_2 stand for material parameters;
- in plane strain condition the fracture strain, obtained by non-incremental forming, can be used to predict the limit strains for incremental forming;

- the proposed approximate theoretical model shows the best agreement with test results in case of bulging heights exceeding 1 mm.

2.2 Numerical Analysis

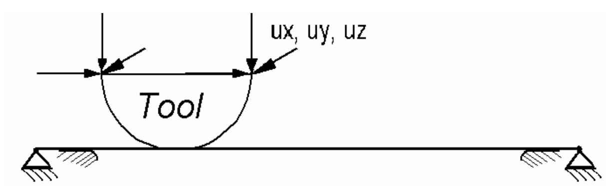
For simulation of the incremental forming process FEA systems ANSYS (developed by ANSYS, Inc.) and LS-Dyna (developed by Livermore Software Technology Corporation) were used. Simulation of ISF process is a complicated task, as the models can not be easily simplified. 3D analyses were performed, because the process can not be simplified to 2D calculation. In addition, the process is not symmetrical even for producing axisymmetrical parts and therefore, a full model has to be modeled. The most serious aspect is the long travel of the tool. Several studies can be found from the literature, where long simulation time appears to be the main obstacle. For example, in some papers it was tried to simplify the calculation by modeling only one sector of axisymmetrical part (He, 2005; Henrard, 2005). However, the simplification causes considerable error.

Due to the nature of the process, several nonlinearities involved in the simulation of incremental forming exist. First, material nonlinearities – the material is while forming in plastic range. Second, geometrical nonlinearity – large displacements are involved. Third, contact calculation has to be performed. In addition, usually large number of elements has to be used and the tool moves along relatively long trajectory. Compared with general sheet metal forming process, the incremental sheet metal forming process has a simple deformation mechanism, but the deformation path of its moving tool in this process is much longer. All the factors mentioned above cause finite element analysis to be complicated and time consuming.

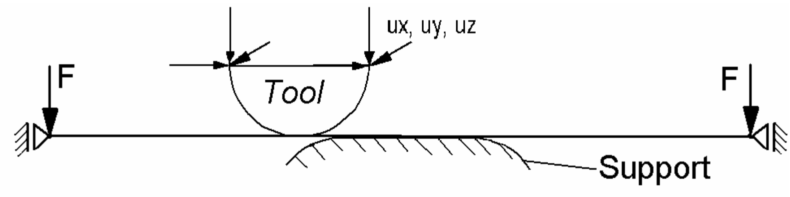
2.2.1 Simulation Model

The basic calculation schemes are depicted in Fig. 2.5. Fig. 2.5 (a) represents the negative forming. As can be seen, the edges of the sheet are fixed, and the sheet is placed on the backing plate that has rounded edges.

Simulation of positive ISF approach is depicted in Fig. 2.5 (b). Here, the sheet is placed on support. The edges of the sheet are pulled down with small force, but they can not move on horizontal plane. The vertical movement of the sheet edges can alternatively be solved using vertical displacement constraints.



(a)



(b)

Fig. 2.5. Calculation schemes of incremental forming processes: (a) forming without support; (b) forming with support.

The tool, the backing plate and the support are considered as rigid objects, because in reality these parts are much stiffer than the workpiece, and this way it takes less time to simulate. The tool was modeled as hemisphere. The backing plate was modeled partially – only the radiuses that will contact the sheet were modeled.

In the current thesis simple rectangular cup (frustum of pyramid) has been used as an example (see Fig. 2.6). For building geometry of the model parametric 3D CAD system ProEngineer (developed by Parametric Technology Corporation) was used, and for control of the tool movement and also for later experimental study, CAM software SURFCAM (Surfware, Inc.) was used. The toolpath data from NC code was translated to macros for FEA preprocessor, by Microsoft Excel procedures written by the author. These macros defined the tool movement using constraints in several load steps.

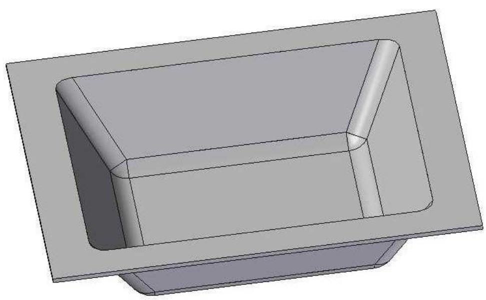


Fig. 2.6. 3D CAD model used in the simulation (Pohlak, 2004 c)

In modeling incremental forming with support, the workpiece-support interface was modeled as well, using contact calculation. Using prestress and contact calculation in sheet fixture area was assumed to be unnecessary.

At first, the simulation using implicit FEA code ANSYS was made. The effects of acceleration were assumed to be insignificant to the results under consideration, thus static analysis was made.

For the simulations two types of 3D shell elements were used. Firstly, shell with 4 nodes, and secondly, shell with 8 nodes. Both of them have nonlinear capabilities and they account for thickness change.

As mentioned above, the simulation of the incremental forming process could be very time consuming. In order to perform simulation the high approximation level has to be used. The two main parameters on which solving time depends most, are the number of nodes/elements (element size) in the model and the number of tool path segments (number of load steps).

Material model used was multilinear isotropic strain hardening anisotropic plasticity. Multilinear stress - strain curve was defined by 9 data points. The modeled sheet was 1 mm thick 99.6% pure aluminum. The properties used in the calculations were as follows: Young's modulus E = 69 GPa; Poisson's ratio υ = 0.33; density ρ = 2.7E-6 kg/mm^3. As ISF process is relatively slow and surfaces were lubricated, temperature effects and accelerations were not considered to be important.

In order to be able to estimate the effect of element count to the solving time two simulations of incremental forming with support were performed. The size of the models was reduced to shorten simulation time – sheet size 50x50 mm, thickness 1 mm. Tool radius was 5 mm and support was rectangular shaped with size of 15x15 mm, corner radiuses 5 mm. Stretching force applied on sheet edge was 1 N. Tool was moved along rectangular toolpath, the size of downward step was 0.5 mm and the total downward moving distance was 2.5 mm.

In the first simulation the element edge length on the tool and support was 1 mm and on the sheet 2.5 mm. Elements with 8 nodes (SHELL93 in ANSYS) were used. The model took 14 hours to solve on 1.6 GHz Intel Pentium 4 PC, but the stress distribution in some areas was unrealistic, which could indicate the need for smaller elements.

In the second simulation the elements on the sheet blank were refined. Now the edge length of 1 mm was used. Other parameters remained the same. This model took 120 hours to solve.

The FEA solver messages indicated that the contact changed too abruptly, and small solving steps were needed. It can be concluded that the main processing time was due to difficulties in contact calculations.

In post processing it was found that thickness values of the sheet after forming were unrealistic, which could indicate the need for using of even smaller elements.

Because of the long duration of simulation on the last case, it was not tried to perform more simulations with smaller elements. So, it was decided to make more thorough simulation of forming without support because it needs less elements and contact regions and therefore takes less time to solve.

In the first simulation of ISF without support, the element edge length on the tool and support was 1 mm and on the sheet 2.5 mm. The FEA model is shown in Fig. 2.7. The elements with 8 nodes were used. The tool radius 5 mm was used and the sheet dimensions were 100x100 mm. The tool was moved along rectangular toolpath, with downward step size 1 mm. The total downward moving distance was 20 mm. The solving of simulation model was found to be very time consuming – it took 72 hours.

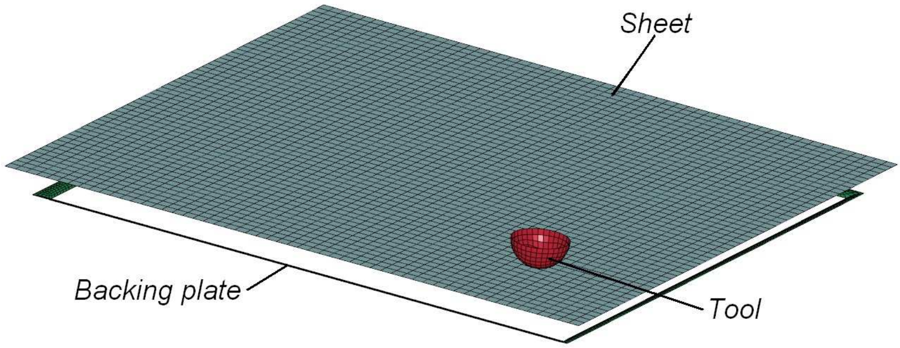


Fig. 2.7. Finite element model (exploded view) used for negative forming simulation

In order to find out how well the model is able to represent the reality, comparison with experimental study was made. In the experimental study, part with similar parameters was produced on 3 axis milling machine tool and tooling designed by the authors. When the part was complete, its geometry was measured (using CMM) and compared with the simulation results. The form deviations of physical model and FEA result were measured ca 2 mm. It was noticed that the results for thickness change were unrealistic (difference was several orders of magnitude), and the thickness varied greatly at adjacent elements.

In the second simulation, the sheet was modeled with 4 nodes (SHELL181 in ANSYS) shell elements, because this was the newer element formulation, and it was believed to give more accurate results. The results were better (more accurate deformations – the form deviations of physical model and FEA result were between +0.439 mm and -1.295 mm), but realistic thickness values were not achieved. It was supposed that the elements are too big for proper thickness calculations.

It was decided to make further simulations of the ISF process using explicit FEA code LS-Dyna. The code is frequently used in sheet metal forming industry.

Similar FEA models were used as described above, except the sheet was modeled with smaller elements (element edge length 2 mm).The tool movement was prescribed by load curves. The best results were obtained by using special metal forming contact type (FORMING_SURFACE_TO_SURFACE).

At first, Belytschko-Tsay shell elements with five integration points through the thickness were used (Hallquist, 2006). However, the validation showed that the deformation is not modeled as accurately as in ANSYS analysis – the form deviations were between +0.9 and -0.9 mm.

In the next simulation, the sheet was modeled using fully integrated shell elements. Now, it took slightly more time to solve, but the results were more accurate.

In simulation with explicit FEA codes an option to speed up the calculations is available by increasing the velocity of the tool or by using mass scaling.

When using this approach, care has to be taken to keep the ratio of kinetic energy vs. deformation energy low. Otherwise fictive inertia effects will influence the results. By using mass scaling, it was possible to shorten the calculation time considerably. The calculation took less than 24 hours.

2.2.2 Results and Discussion

The validation of results of last simulation showed that the form deviations of physical model and FEA result were between -0.8 mm and +0.74 mm (see Fig. 2.8). The largest deviation was in step-down area of the tool. It could be caused by fictional inertia effects (too much mass scaling) or the initial contact and step-down of the tool is too abrupt.

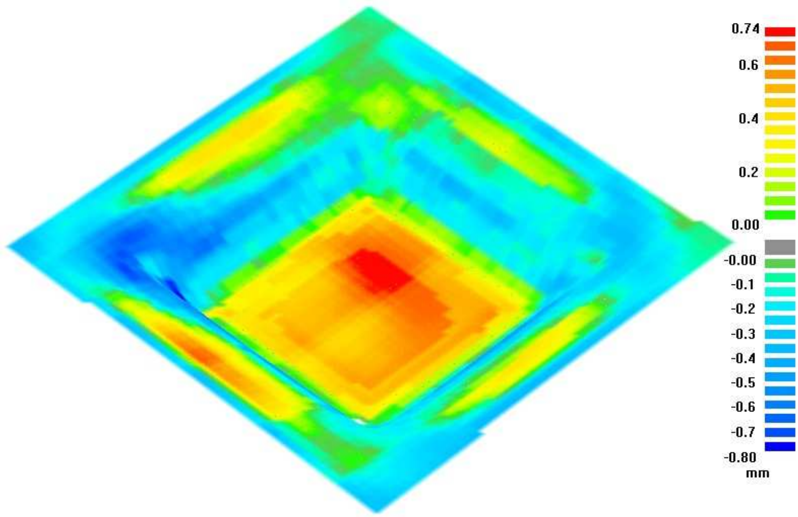


Fig. 2.8. Comparison of physical model and FEA results (Pohlak, 2004 c)

The deviations in other areas are most likely due to too approximate material model, inadequate boundary conditions and too large element size. It is possible to make results more accurate by modeling of sheet fixture using contact calculation here also, but this procedure would increase computation time considerably. The second option, to make model more adequate, is by increasing element number (using smaller elements), but it will surely increase computational time.

The equivalent stress plot, shown in Fig. 2.9, indicates that the highest stresses are at forming region and contact area. The lowest stresses are at the central area of the part. It is in agreement with engineering judgment of the author, and proves that the model behaves in expected manner.

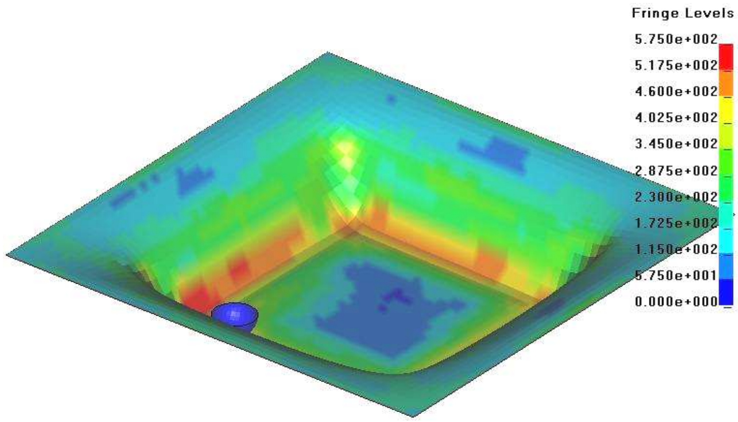


Fig. 2.9. Stresses in the part

An important factor in sheet metal forming, especially ISF, is the thickness after forming. There were some problems predicting thickness values with ANSYS. However, LS-Dyna modeled the thickness change of shell elements in the process relatively well. The thickness distribution is shown in Fig. 2.10. There is a good agreement between simulation results and measured values. It is worth to mention, that the thickness of real part varies slightly, because of small tool radius and large step size. However, the model used is not able to predict this due to too large element size (elements are larger than the step size).

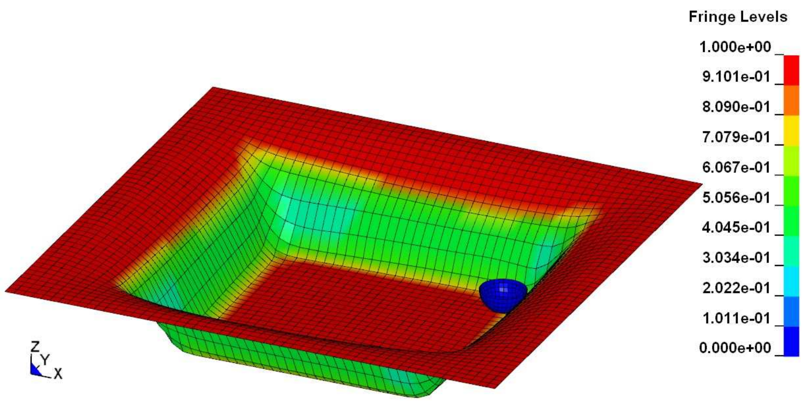


Fig. 2.10. Final thickness plot

The question of choosing between implicit and explicit FEA code is sometimes raised. Generally, dynamic, large scale and more non-linear processes are better solved using explicit codes. On the other hand, implicit codes are better in case of quasi-static processes. For best results, both options are combined – dynamic sheet metal forming processes are simulated with explicit code, and then slower processes, for example springback after unclamping, are modeled using implicit code. Modern sheet metal forming FEA systems are usually able to use both solvers (Lenard, 2002). LS-Dyna, used in current study, has also capability of switching between explicit and implicit mode (Hallquist, 2006). The possibility to simulate the springback effect after removing redundant areas after forming is especially useful. However, this is not thoroughly studied by the author, and will be focused on in the future.

The post-processing of LS-Dyna analysis results was performed using LS-PREPOST (developed by Livermore Software Technology Corporation). It has built in capability for sheet metal forming of using FLD. This capability is very useful in industrial applications, where it allows optimizing the shape and process parameters to avoid failures in forming. The tool visualizes the potential risk areas with different colors, e.g. cracks – red, risk of cracks – yellow, wrinkles – magenta, etc. It is especially important that the data for FLD is based on actual material testing with ISF, because the FLDs of conventional forming and ISF are different. The formability analyzing tool turned out to be beneficial in current study.

LS-Dyna provides the capability of automatically refining elements, if mesh is distorted. It is called adaptive mesh refinement. In classical problem, it is useful when simulation is started with large elements, then the elements are automatically refined if specified criteria are met, and calculation resumes. However, the calculation time in explicit FEA codes depends mostly on element size, not only the number of elements. In adaptive mesh refinement procedure, after the refinement step, the solver takes one calculation step back and resumes the calculation from that point. As experiments showed, this may cause the total simulation time to increase. It is reasonable to use equal size elements (with proper size) from the beginning of the calculation.

The FEA provided practical results for prediction of forming forces. This is discussed in more detail in Chapter 4.

The simulation of ISF with support needs further attention in the future. The principle of the process requires the consideration of the ironing effect (the sheet thinning when pressed between tool and support). Currently, thin shell elements are not able to model this adequately and therefore, thick shells have to be used instead. Using of thick shells in simulation of ISF is planned in the future.

The main problem of simulations was the duration of the calculations. In fact, it takes much less time (>100x) to set up experiments and produce parts than to simulate the process. This is the main restriction in using the FEA for optimization of the process.

It can be concluded from validation that FE model needs further refinement; smaller elements have to be used. To achieve more accurate and less time consuming simulations some special purpose FEA code could be needed that has procedures fine tuned for incremental forming.

As more detailed data of the influence of process and product parameters is needed, and FEA takes too long to solve, experimental studies were made in addition to simulations. The experimental study is described in the following chapter.

2.3 Conclusions of the Chapter

1. The Iseki's theoretical model for describing ISF process has been improved by introducing the influence of plastic anisotropy. A simplified theoretical model was found befitting for estimating force components in the case of bulging heights exceeding 1 mm. The influence of the plastic anisotropy on material formability is found to be significant.
2. Some concepts used, can be formulated as: in test design corresponding to uniaxial stretching conditions the influence of plastic anisotropy should be considered; in test design corresponding to biaxial stretching conditions, the final geometry of the formed sheet can be chosen similar to traditional FLD test (hemispherical punch test).
3. Some strategies for determining forming limit diagram in ISF process were studied. The test procedures were designed for determining FLD in ISF process.
4. The ISF process was modeled using FEA software systems ANSYS and LS-Dyna. Simplified processes were modeled: the part was a simple frustum of pyramid; vertical step size was much bigger than in real production situation. The thin shell elements were used in FEA. Better results were achieved by using explicit FEA solver LS-Dyna.
5. The simulation process involves several nonlinearities, and the loading path is complicated. It caused the simulation to be time consuming – the simulation of the forming a part that can be produced within 10 minutes, took approximately 24 hours on a standard PC. Thus, simulation process is too time consuming and cannot be used for optimization of parts in real production.
6. The numerical models were validated by comparison with experimentally produced part. The obtained numerical and experimental results were found to be in a good agreement.

3 EXPERIMENTAL STUDY

The mechanics of the process is fairly complex. Theoretical study and numerical analyses provided some information about several aspects, but many problems were left unsolved. The experimental study to determine the influence of most important process and product parameters to quality indicators was performed. In the experimental study both, forming with support and forming without support, were investigated.

3.1 ISF without Support

To achieve accurate form of part in ISF without support, the sheet should be supported close to the deformed area. Otherwise the sheet bends through and form deviation occurs. It means that if the part has complicated geometry then the sheet holder should also have similar shape and this technology loses some of its flexibility as special sheet holder has to be prepared for each part. To find ways to avoid this, some process and product parameters were studied in experiments in which sheet was deformed at the distance of 10 mm from the sheet support.

3.1.1 Methods and Materials

Model

Simple rectangular cup (frustum of pyramid) was chosen for the geometry of the test part (Fig. 3.1). The formed volume was approximately 80x80x40 mm.

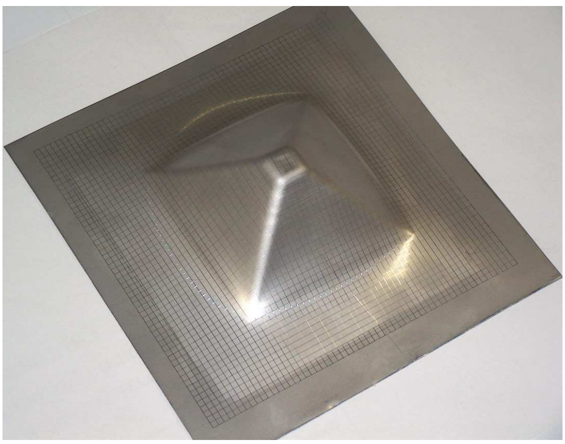


Fig. 3.1. Manufactured test part (Pohlak, 2004 d)

Material

The material of the blank used in this study was aluminum alloy EN AW-1060 (specified in EN 573:2004), contains (min) 99.6% Al, (max) 0.25% Si, (max) 0.35% Fe, (max) 0.05% Cu, (max) 0.03% Mn, (max) 0.03% Mg, (max) 0.03% Ti, (max) 0.05% Zn, (max) 0.05% V. Density of the material is 2705 kg/m^3, tensile strength 97 MPa, yield strength 90 MPa, modulus of elasticity 68.9 GPa. The thickness of the sheet was 1 mm.

Design of Experiments

The most efficient way to analyze the influence of some variables on measurable outputs is by using factorial design of experiments (Montgomery, 2001).

Three input parameters have been used as follows:

- Tool radius, R (R_{min} = 3 mm; R_{max} = 10 mm)
- Vertical step size, p_z ($p_{z\ min}$ = 0.1 mm; $p_{z\ max}$ = 1 mm)
- Wall draft angle, α (α_{min} = 30º; α_{max} = 60º)

The parameters were selected based on previous experiences and information from the literature. These three parameters were considered to be most important and easy to control.

Two level factorial design with one experiment at the center of the model was made, so the total number was 9 experiments.

On every minimum - maximum combination of these parameters several output indicators were measured, the most important of which are as follows:

- Wall thickness
- Flatness deviation of non-horizontal walls
- Surface roughness on processed surfaces
- Total form deviation of part

For product design, these indicators are the most essential, in addition, they are easy to measure.

The function to estimate the effect of process input parameters x_1, x_2 and x_3 (corresponds to R, p_z and α respectively) to the process output indicators y_i is described as follows:

$$g(y_i) = a_0 + \sum_{i=1} a_i x_i + \sum_{i=1} \sum_{j=1} a_{ij} x_i x_j \,, \tag{3.1}$$

where a_i and a_{ij} are the coefficients estimated from experiments; $g(y_i)$ is some preselected transformation function.

Experimental Set-up

Fixture for producing parts is shown in Fig. 3.2. It consists of a base and a blank holder. The base is fixed onto machine tool table. The blank holder is connected with the base by bolts, ensuring the fixed position of the sheet blank.

The experiments were made on vertical 3 axis CNC machining centre Dyna EM-3116 from DYNA Mechtronics Inc.

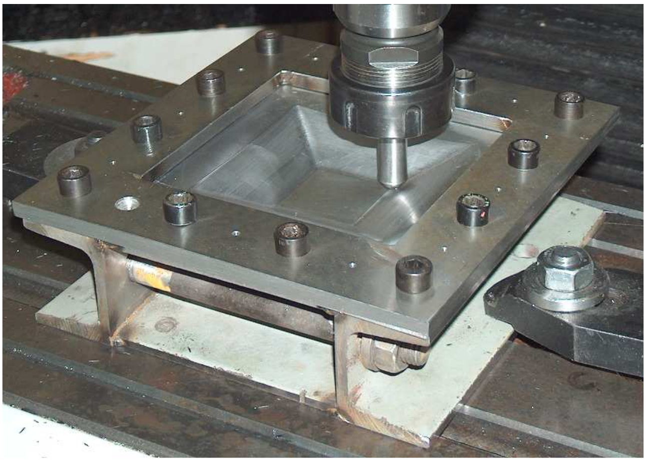


Fig. 3.2. ISF fixture (Pohlak, 2004 d)

Tools

In the experiments of ISF without support, three different tools with radius 10 mm, 15 mm and 30 mm were used (Fig. 3.3). The tools were made of tool steel, afterwards hardened and polished.

Fig. 3.3. Tools used in the study

Toolpaths and Machining

For preparing the toolpaths for CNC controller, commercial CAM system SURFCAM from Surfware, Inc. was used.

In the study uni-directional toolpaths were used. The step-down was made at the corner of the pyramid.

During the experiments the tool was not rotating, it was sliding on the surface of the sheet that was lubricated with mineral oil.

The feed rate of the tool was kept constant throughout the experiments – 2000 mm/min.

Measurements

The wall thickness was measured using digital indicators. Flatness deviation was measured with coordinate measuring machine Mitutoyo Strato, produced by Mitutoyo Corporation. Surface roughness was measured using portable surface roughness measuring system Surtronic 3+, produced by Taylor Hobson Ltd. Form deviation was measured with 3D laser scanner Replica, produced by 3D Scanners Ltd.

3.1.2 Results

The range of responses measured is listed in Table 3.1. The data can be used as approximate guide in process selection or design.

Table 3.1. Minimum and maximum values of measured responses

Response	Min value	Max value
Thickness, mm	0.46	0.86
Flatness, mm	0.110	0.390
Surface roughness Ra, μm	0.4	4.4
Total form deviation, mm	3.585	7.226

The analysis of the results was made. The regression models for most significant parameters are shown below.

Thickness:

$$t = 0.097 + 0.0126\alpha \tag{3.2}$$

Flatness:

$$e_f = 0.2895 - 0.0077R + 0.0936p_z + 0.0031\alpha + 0.0128Rp_z - 0.0005R\alpha - 0.0041p_z\alpha \tag{3.3}$$

Surface roughness:

$$\log_{10}(SR) = 0.6008 - 0.0354R - 0.4499p_z - 0.0123\alpha + 0.0224p_z\alpha \tag{3.4}$$

Total form deviation:

$$e_{fd} = 6.3236 + 3.6503p_z - 0.0288\alpha - 0.0729p_z\alpha \tag{3.5}$$

3.1.3 Discussion

In the study the two level design of experiments was used. The analysis of the results indicated that more detailed study to achieve more accurate models may be required.

The experimental study was designed so, that the sheet was deformed at the distance of 10 mm from the sheet support. The purpose of that was to investigate the forming "in the air", i.e. without special support. In this case, deflection of the sheet near supporting areas of the fixture occurs. It is important aspect when universal tools are used.

Fig. 3.4 shows the cross section of the part produced using ISF without support. In the figure, the section of "ideal" part, i.e. without deflection, is displayed. Note the considerable deflection near upper edge, i.e. where sheet fixture ends.

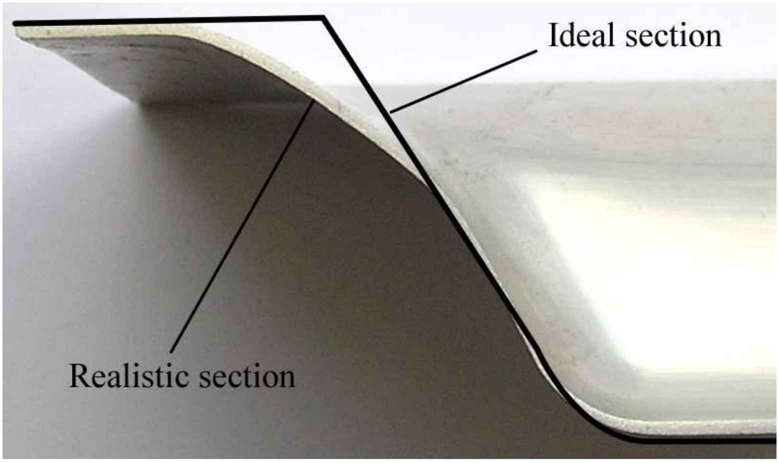


Fig. 3.4. Ideal and realistic section of the part

The majority of form deviations in current study occurred due to deflection of unsupported surfaces. This can be seen from deviation plot in Fig. 3.5. It means, that the deviations can be minimized by using supports or backing plate. The second most important source of form deviations is usually elastic spring-back of material. It presents a serious problem particularly in forming of elastic materials, e.g. stainless steel.

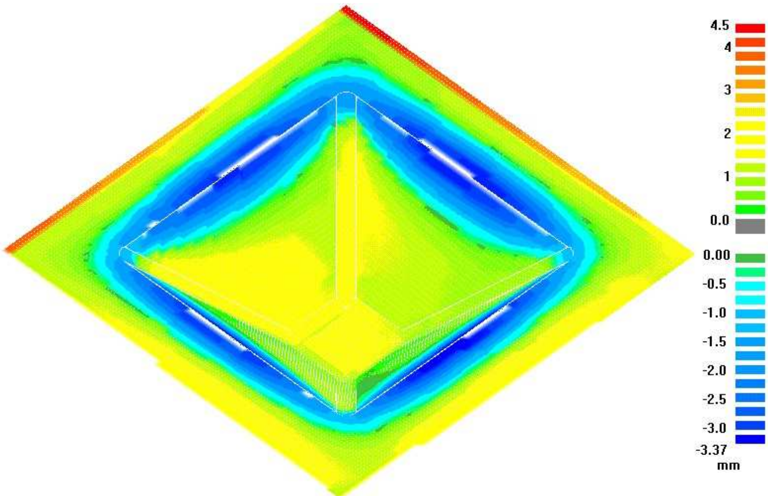


Fig. 3.5. Deviation plot of manufactured part and initial 3D CAD geometry (Pohlak, 2004 d)

The influence of draft angle and step size on total form deviation is described in Fig. 3.6. Apparently, there is an interaction between p_z and α. It makes the minimization of deviation more complicated. The optimum value of p_z depends on geometry and in realistic applications should change in different areas of the part. Today, no commercial CAM system provides the capability of generating toolpaths with automatically changing of p_z.

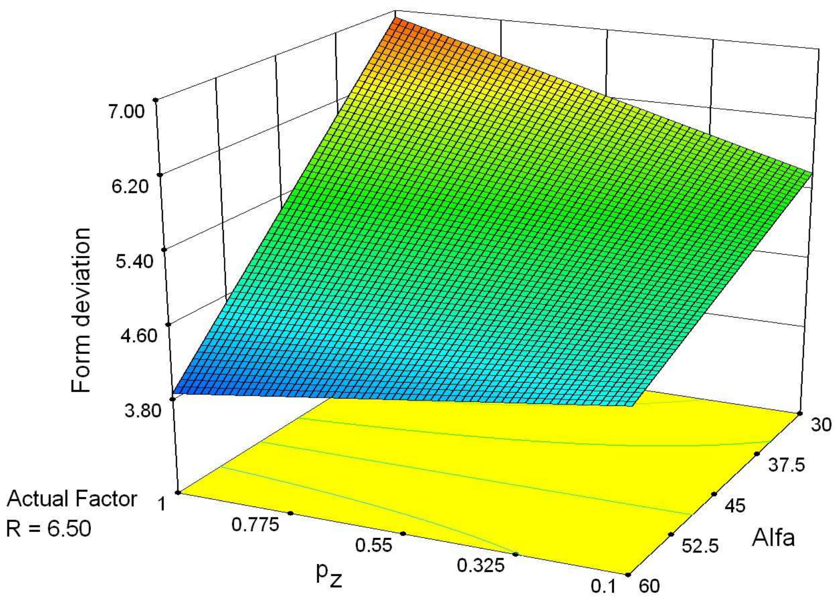


Fig. 3.6. Influence of draft angle and step size on form deviation

One drawback of ISF is the dependence of wall thickness on wall draft angle. Steeper the walls, thinner the sheet will be. In extreme cases, the deformation is too high and the sheet will break. As stated earlier, the thickness in ISF obeys the sine law. In Fig. 3.7 the relationship of draft angle and wall thickness is shown. Note, that the diagrams are close to the values proposed by the sine law (1.1).

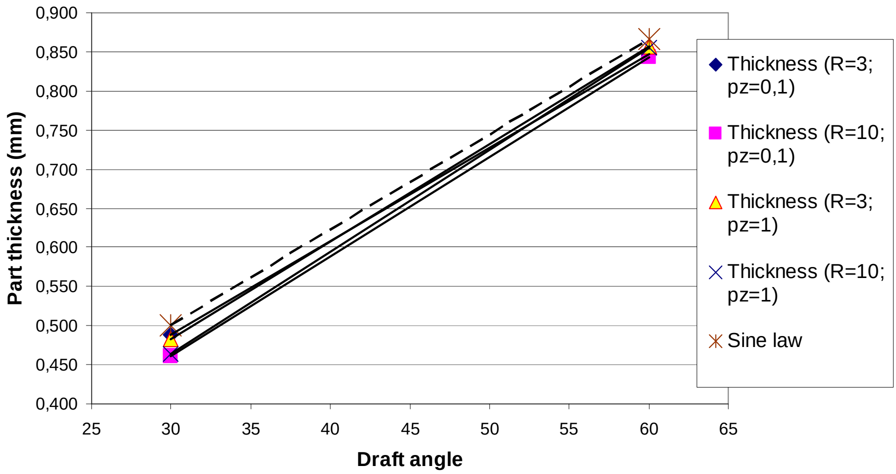


Fig. 3.7. Draft angle and part thickness relationship (Pohlak, 2004 a)

The surface roughness on the tool side depends mostly on vertical step size and tool radius. On the other side, roughness also depends on grain size of the alloy and deformation magnitude – if large grain alloy is heavily deformed, the surface will have visible texture. On the tool side, the tool irons the surface leaving wavy surface (Fig. 3.8). Depending on lubrication used, the hard particles (small pieces of blank, tool or other) may draw visible lines on the surface.

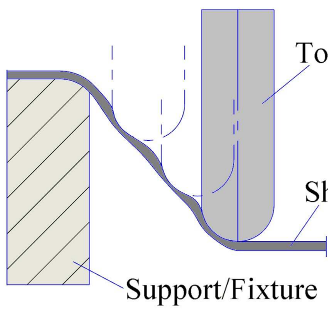


Fig. 3.8. Tool marks on the surface

On surfaces designed flat, the flatness deviation was measured. The relationship of the flatness deviation and the tool radius is described in Fig. 3.9. As can be seen, tools with larger radius produce parts with smaller flatness deviation. However, the results indicate that the significance of factors is relatively low and could be due to noise. One cause could be the small area where the flatness was measured (size constraints of ISF fixture).

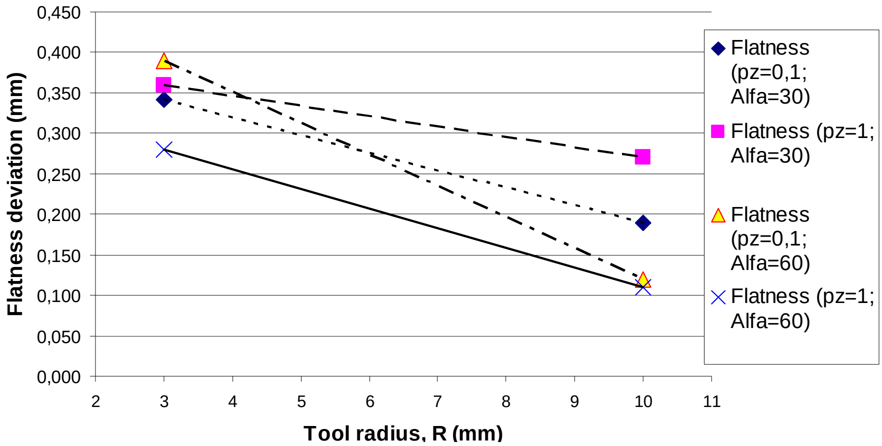


Fig. 3.9. Tool radius and flatness deviation relationship (Pohlak, 2004 a)

3.2 ISF with Support

From the literature several papers describing experimental study of different aspects of incremental forming without support can be found. However, not so many works are concerning incremental forming with support and only some of them introduce models for estimating properties of the product. Forming with support is more complex as more parameters are involved. It allows achieving better accuracy and more complicated geometry.

For filling the gap in knowledge about ISF process, an experimental study was performed.

3.2.1 Methods and Materials

Model

To study the process simple models with pyramid shape were used (see Fig. 3.10). In the process, a structure supporting whole pyramidal surface for better stability was used.

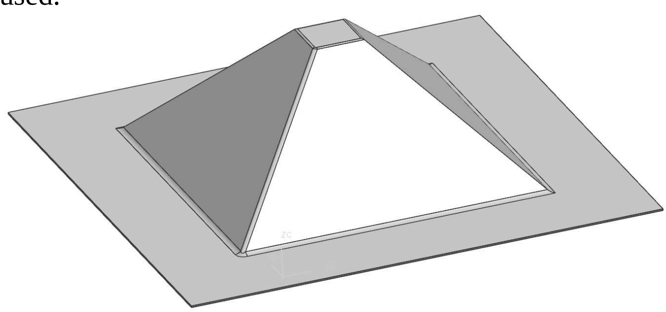


Fig. 3.10. Geometry of the model used in the experimental study

Material

The material of the blank was aluminum alloy EN AW-1050A (specified in EN 573:2004), contains (min) 99.5% Al, (max) 0.25% Si, (max) 0.4% Fe, (max) 0.05% Cu, (max) 0.05% Mn, (max) 0.05% Mg, (max) 0.05% Ti. Density of the material is 2705 kg/m^3, tensile strength 110 MPa, yield strength 103 MPa, modulus of elasticity 69 GPa. The thickness of the sheet used in the study was 1 mm.

Design of Experiments

After analyzing the literature and preliminary experimental study, it was decided to do more thorough experimental investigation of the influence of some parameters that affect the final geometry of the product the most. There are many parameters that are interesting to researchers in the field, but because of the economical considerations and time constraints, four parameters were chosen as follows:

- Tool radius (R)
- Vertical step size of the tool (p_z)
- Wall draft angle of final geometry (α)
- Stretching force – vertical force pushing the blank onto the support (F_s)

First three of the parameters were considered to be the most important by the knowledge gathered from preliminary experiments and literature. The application of stretching force in ISF has not been found in literature. However, the stretching force was considered to be important enough and the influence of it was investigated.

As the most efficient way to analyze the influence of some variables on measurable outputs is by using factorial design of experiments (Montgomery, 2001), two level factorial design with four experiments at the center of the model were made, so the total number was 20 experiments.

The different tool radiuses were implemented by preparing three different tools, the step size variation by different toolpaths (defined in CAM system), the draft angle by toolpaths and different supports, and the stretching force by adding extra weights to the sheet holder. As extra weights with precisely needed mass were not available, the average mass was slightly lower than the mathematical average.

The values of variables are shown in the Table 3.2.

Table 3.2. The values of design variables in experimental study

Design variable	Minimum level	Maximum level	Mean level
R, mm	5	15	10
p_z, mm	0.1	1	0.55
α, degree	30	60	45
F_s, N	0	205	89

Output parameters of the study are as follows:

- Flatness deviation on different surfaces
- Surface roughness on different surfaces
- Forming force components
- The characteristics of step-down line

For each of them a regression model was determined.

The ISF Fixture

The ISF fixture, utilized in the study, is shown in Fig. 3.11. It consists of a base plate onto which a support is attached. Two linear guide bars are attached to the base plate. On the bars, linear ball bearings with sheet holder are mounted. The linear guide bearings allow only vertical movement of the sheet holder. The sheet is fixed to the holder by bolts.

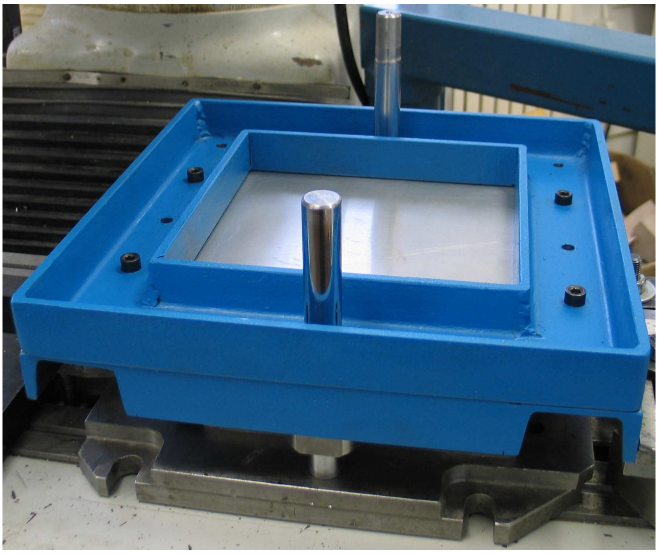


Fig. 3.11. The ISF fixture for forming with support

Supports

Generally, the selection of material for support depends on the size of the gap between the tool and support, material of the sheet to be processed, the accuracy of the toolpaths and the number of parts to be produced, etc. In current study, the supports were made of medium density fiberboard (MDF). The material was chosen because in the study soft aluminum was formed and the number of parts produced with one support was low. In addition, the machining of MDF is easy and fast.

The blank for support was made by gluing several pieces of MDF together. For gluing the pieces epoxy glue was used. Fig. 3.12 shows the supports after machining operation.

The supports were attached to the base plate of the ISF fixture with bolts.

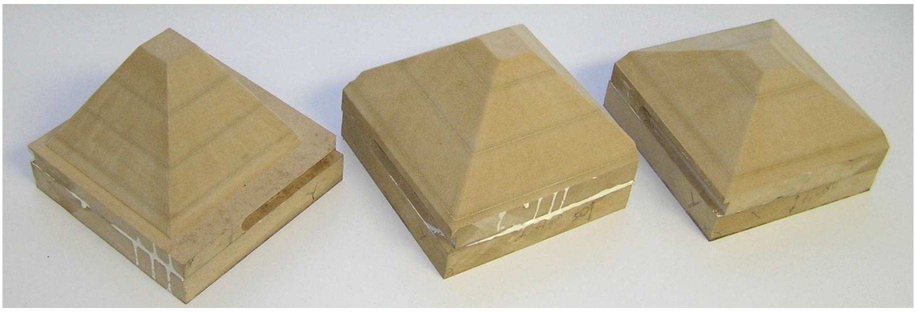


Fig. 3.12. Supports after machining

Tools

In the experiments three different tools (radius 10 mm, 15 mm and 30 mm) with simple hemispherical tip were used. Tools, made of tool steel, were hardened and polished.

Toolpaths and Machining

The experiments were made on 3 axis CNC machining centre Dyna EM-3116 from DYNA Mechtronics Inc.

For preparing the toolpaths for CNC controller, commercial CAD/CAM/CAE system Unigraphics NX4 (from UGS Corp.) was used.

In the study bi-directional toolpaths were used in order to avoid additional geometry deviations induced by part rotation.

During the experiments the tool was not rotating, it was sliding on the surface of the sheet that was lubricated with mineral oil.

The feed rate of the tool was kept constant throughout experiments – 2000 mm/min.

The location of step-down motion of the tool was chosen at the flat surface in order to be able to measure better the step-down line characteristics.

Measurements

During the forming operation forces were measured. All other measurements were performed after the forming.

Geometric characteristics of the parts were measured on the surfaces A, B, C and D (see Fig. 3.13). The tool makes downward step always at the same position, on Fig. 3.13 it is shown with the dotted line.

The blank was positioned into the fixture so that the rolling direction of the sheet coincided with *x*-axis of the machine tool. This way the anisotropy of the blank was taken into account.

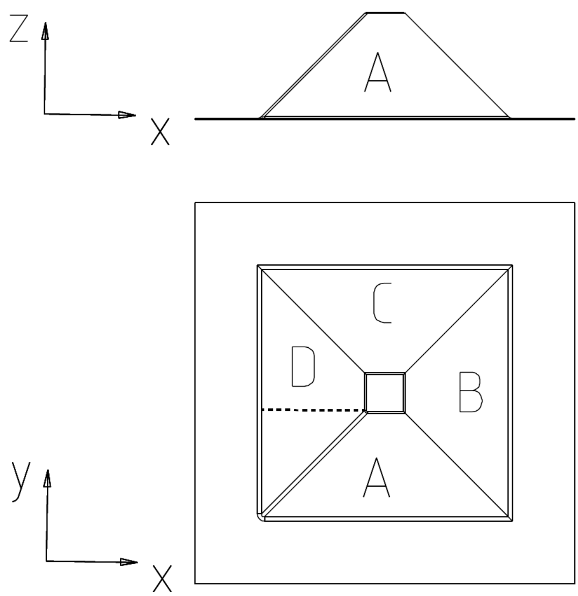


Fig. 3.13. The notation of surfaces

Force Measurement

Forming force is very important process parameter in metal forming. The force required for sheet forming limits the equipment needed.

The force measuring set-up consists of ISF fixture that is mounted on top of the load cell. The piezoelectric loadcell from Kistler Instrumente AG was used. The loadcell is able to measure the forces in three perpendicular directions. In addition, the measuring system includes charge amplifiers, data acquisition cards and a PC. The sampling rate in force measurement was 50 Hz.

The data acquisition and analysis in force measurement was performed with software Catman Easy (from Hottinger Baldwin Messtechnik GmbH). Further data processing and analysis was performed using MATLAB (from The MatWorks, Inc).

Flatness

One easy way to characterize accuracy of forming process is by measuring flatness deviation on non-horizontal surfaces. In the study the flatness of surfaces marked with A, B, C and D on Fig. 3.13 was measured.

In Fig. 3.14 the top view of the test part with the section highlighted is presented. As can be seen, the real surface is convex, while the ideal is flat.

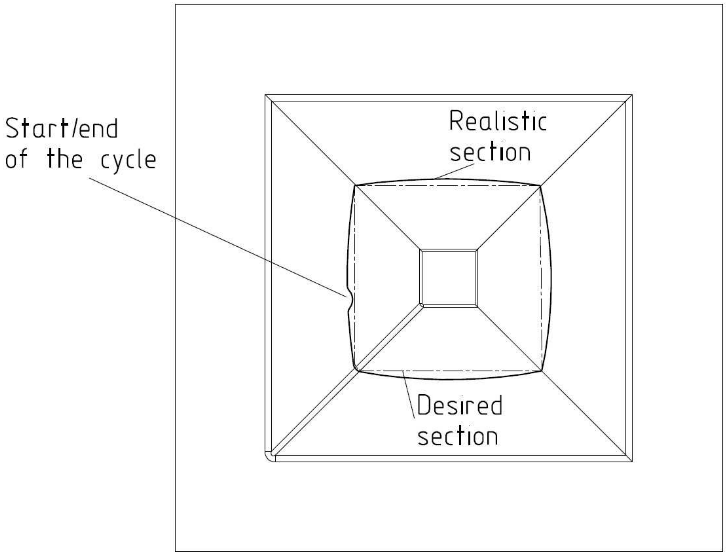


Fig. 3.14. The section of the part (top view)

The flatness was measured with coordinate measuring machine TESA Micro-Hite 3D, produced by TESA SA.

Surface Roughness

Surface quality is an important parameter in evaluation of suitability of forming processes. The preliminary experiments show that in ISF surface quality can greatly vary depending on the process parameters. It is evident, that in order to achieve higher surface quality, the process will be more time consuming.

In the study the surface roughness Ra (arithmetical mean roughness according to ISO 4287:1997) of surfaces marked with A and B in Fig. 3.13 from both sides, tool and support side, was measured. The measuring direction was perpendicular to toolpaths.

Surface roughness measurements were made using surface finish and form measurement system Surtronic 3+, produced by Taylor Hobson Ltd.

The Step-down Line

The place where tool makes a step downwards after each cycle forms a visible defect. If the toolpath is such that the cycle ends near the end of previous cycle, the so-called step-down line forms. This is the case when the toolpaths are prepared with general CAM software, i.e. at present there is no commercially available CAM system that is able to disperse the step-down points eventually on the part and avoiding the defect. For this reason the elimination of the effect is important.

In Fig. 3.14 the section of the part is shown. As can be seen, at the place where tool moves step downwards (start and end of cycle), is a twist. Geometry at this region was studied using CMM and surface finish and form measurement system Surtronic 3+. The measurements were done in perpendicular direction to the step-down line.

3.2.2 Results

Measured responses were as follows:

- Flatness - surfaces A, B, C and D
- Surface roughness Ra – surface A, upper side; surface A, lower side; surface B, upper side; surface B, lower side (perpendicular to toolpaths)
- Surface roughness parameters Ry (maximum peak) and Ra of step-down line
- Surface roughness Ra along toolpath
- Load components F_x, F_y and F_z
- Depth of step-down line

The range of responses measured is listed in Table 3.3.

Table 3.3. Minimum and maximum values of measured responses

Response	Min value	Max value
Flatness (surface A), mm	0.467	4.900
Flatness (surface B), mm	0.301	5.330
Flatness (surface C), mm	0.473	5.297
Flatness (surface D), mm	0.448	5.230
Surface roughness from tool side (surface A), µm	1.3	8.7
Surface roughness from tool side (surface B), µm	1.3	9.4
Surface roughness from support side (surface A), µm	2.9	12.4
Surface roughness from support side (surface B), µm	2.6	17.5
Maximum force along *x*-axis, N	71	343
Maximum force along *y*-axis, N	66	319
Maximum force along *z*-axis, N	295	1017
Surface roughness Ra (across step-down line), µm	2.3	10.0
Surface roughness Ry (across step-down line), µm	6.3	34.6
Surface roughness Ra (along toolpath), µm	0.3	1.4

After the measurements ANOVA analysis was performed. The regression models for most significant parameters are shown below.

Flatness of surface A:

$$e_{fA} = (0.3657 + 0.0184R - 0.5793p_z + 0.0078\alpha - 0.0003F_s + 0.0106p_z\alpha + 2.82\cdot10^{-5}\alpha F_s)^{-2} \quad (3.6)$$

Flatness of surface B:

$$e_{fB} = (2.2926 - 0.0782R + 1.5284 p_z - 0.0229\alpha - 0.0012F_s + 0.0011R\alpha - 0.0223 p_z\alpha)^2 \quad (3.7)$$

Average flatness:

$$e_{fave} = (2.5367 - 0.0809R + 1.3197 p_z - 0.0257\alpha - 0.0011F_s + 0.0012R\alpha - 0.0208 p_z\alpha)^{-2} \quad (3.8)$$

Surface roughness from tool side (surface A):

$$SR_{AUpper} = 1.5988 + 0.0155R + 6.1375 p_z - 0.3242Rp_z \quad (3.9)$$

Surface roughness from tool side (surface B):

$$SR_{BUpper} = \frac{1}{0.3726 + 0.0204R - 0.3092 p_z} \quad (3.10)$$

Maximum force along *x*-axis:

$$F_x = 256.8 + 17.17R - 92.5778 p_z - 2.9681\alpha - 0.2595R\alpha + 2.91 p_z\alpha \quad (3.11)$$

Maximum force along *y*-axis:

$$F_y = 64.0532 + 26.1339R + 111.5527 p_z - 0.2382\alpha - 5.2865R\, p_z - 0.3705\, R\alpha \quad (3.12)$$

Maximum force along *z*-axis:

$$F_z = 398.6627 + 20.3935R + 317.885 p_z - 4.44\alpha + 0.7327F_s \quad (3.13)$$

Surface roughness parameter Ra across step-down line:

$$SR_{RaLine} = 2.7553 + 0.0226R + 8.3722 p_z - 0.3256R\, p_z \quad (3.14)$$

Surface roughness parameter Ry across step-down line:

$$SR_{RyLine} = 42.6441 - 0.5413R + 5.4278 p_z - 0.3607\alpha - 0.0344F_s + 0.0412 p_z\, F_s \quad (3.15)$$

3.2.3 Discussion

In the study the two level design of experiments was used. However, the analysis of the results indicated that for some parameters "lack of fit" is present and therefore, three level design could be preferred to achieve more accurate models.

The statistical analysis of the results allows evaluating the influence of the factors on the product and process characteristics, thus achieving better quality of products by controlling the important factors.

Generally, the ISF technology can be used in applications where the accuracy of form and dimensions is not the most important factor. As experiments show, the form deviation can be several millimeters. The experimental study about form deviation is described in section 3.1. It has been studied by other researchers as well. For example Ambrogio et al. (Ambrogio, 2007) created experimental models for deviation compensation in ISF without support.

In the case of the parts with complicated geometry, there is a chance, that the form deviations may not be noticed visually. However, if a surface that has to be flat is present, then the flatness deviation is easily detectable. Author of the current study investigated experimentally the effect of the factors on flatness deviation in ISF with support.

After statistical analysis of the results the effects can be visually examined using Pareto chart and half-normal plot of effects. The use of latter is more suggested (Montgomery, 2001).

On Pareto chart, the longer is the bar, the more significant is the corresponding factor. On the Pareto chart, two different t-limits are plotted – based on the Bonferroni corrected t and a standard t. Effects that are above the t-value limit are possibly significant (with 5% risk level). Effects above Bonferroni Limit are almost certainly significant (for details about Bonferroni method refer to (Montgomery, 2001)). Effects that are below the t-value limit are not likely to be significant.

In Fig. 3.15 the Pareto chart is presented, where statistically significant effects of flatness of surface A are shown. Note that in Figs. 3.15-3.26 A corresponds to tool radius (*R*), B – vertical step size (p_z), C – wall angle (α) and D – stretching force (*Fs*). The combinations AB, BC etc denote the interactions between the factors.

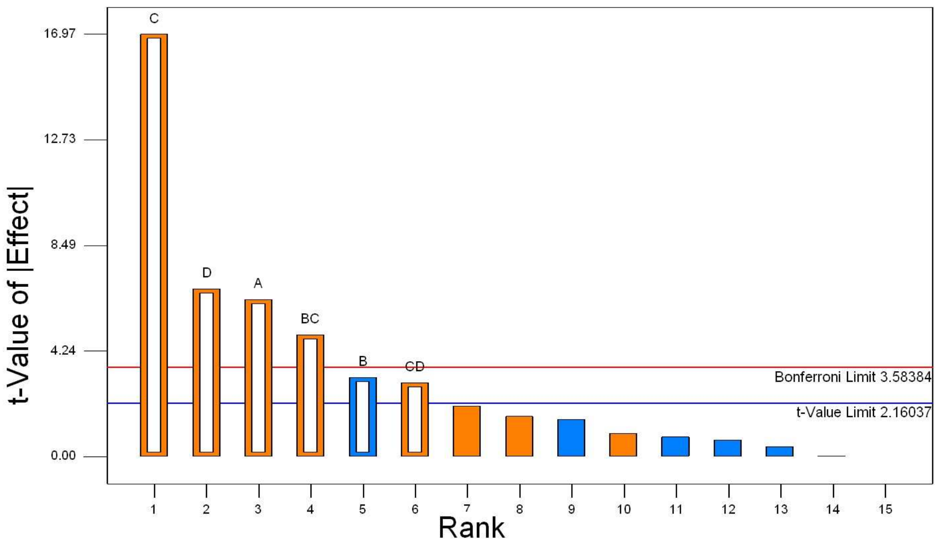


Fig. 3.15. The significant factors for flatness of surface A

On half-normal probability plot, large absolute values show up as outliers in the upper right-hand section of the graph. The effects that are negligible are normally distributed and will tend to fall along a straight line on the plot (the line on the plot always passes the origin), while significant effects will have nonzero means and will not lie along the line (Montgomery, 2001).

The Half normal plot of effects for flatness of surface A is in Fig. 3.16.

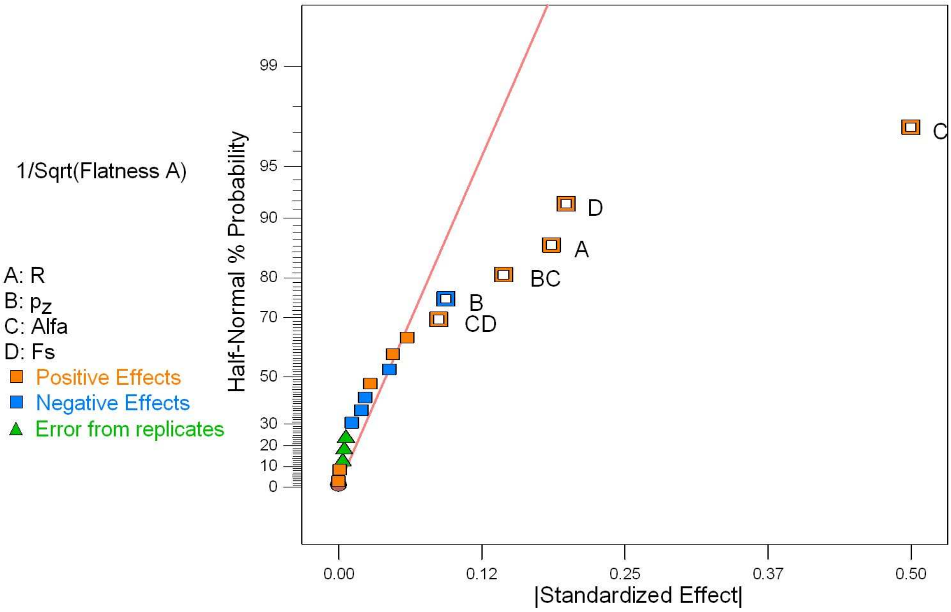


Fig. 3.16. Half normal plot of effects for flatness of surface A

As can be seen from Table 3.3, the flatness varies in wide range (more than 10 times) whereas the lowest values are ca 0.5 mm. So, the flatness deviation could be one factor that excludes from using ISF technology in applications that require more accurate form.

The study indicated that the wall angle is the most significant factor in the flatness deviation (see Fig. 3.15 and Fig. 3.16). In this situation, one of the influencing factors may also be the low stiffness of the sheet holder – it uses two linear guide bearings (see Fig. 3.11) instead of four utilized in commercial ISF systems.

As discovered, the accuracy of the parts made by ISF is fairly low – the form deviations could be even several millimeters in parts with dimensions of 100x100x100 mm. So, if parts are not accurate, they might be used successfully in applications where the appearance is more important than the accuracy, i.e. emphasis on industrial design. Analyzing surface quality after the forming process could answer the question.

The surface texture at tool side is induced by the tool – it can be seen even without detailed analysis that the most important factors are the tool radius and the distance between subsequent toolpath lines. The significant factors for surface roughness at the tool side on surface A and B are shown in Fig. 3.17 and Fig. 3.18 respectively. As can be seen, in surface A, the interaction of factors A

(R) and B (p_z) is significant, while in surface B it is not. The reason for that is not fully known. The effect of the interaction is illustrated in Fig. 3.19.

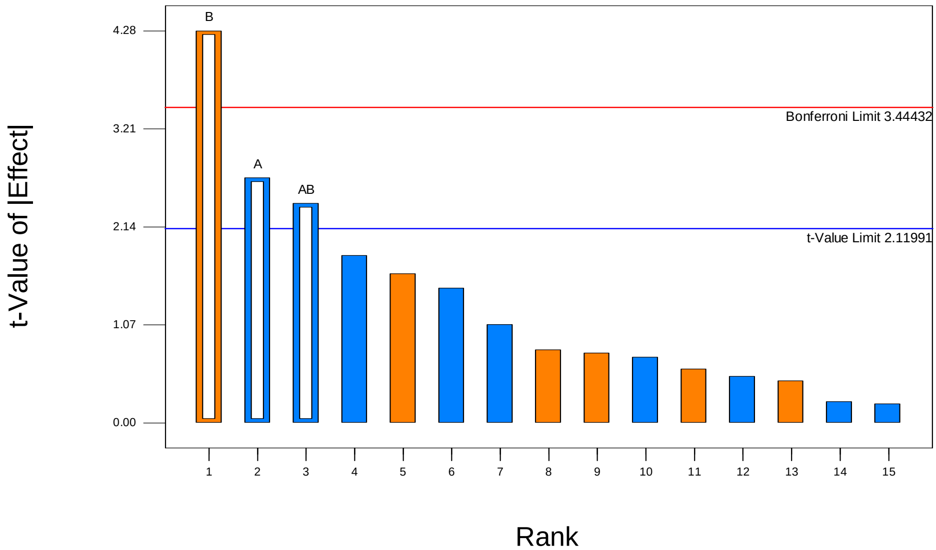


Fig. 3.17. The significant factors for surface roughness of surface A

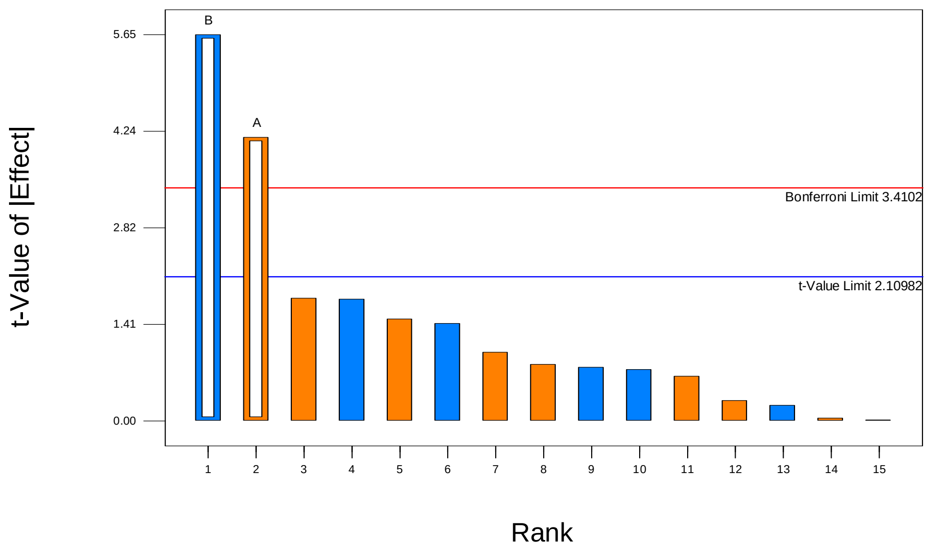


Fig. 3.18. The significant factors for surface roughness of surface B

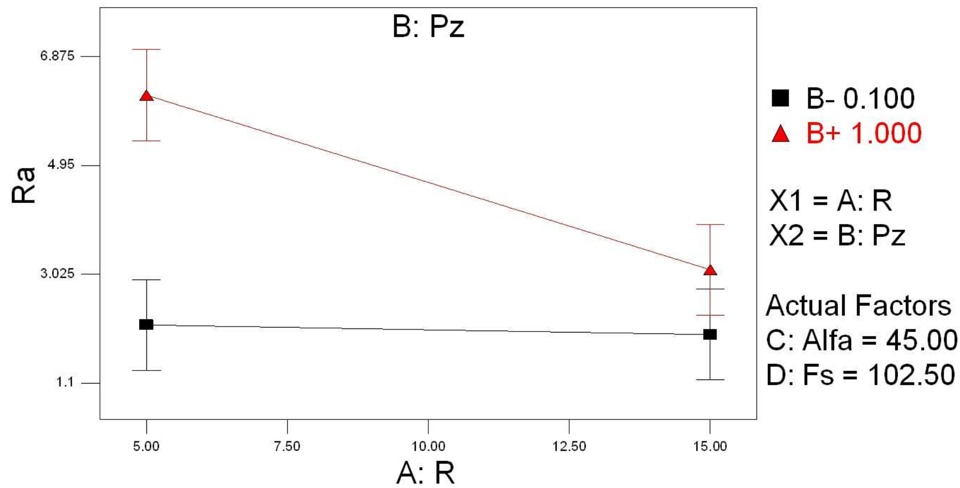


Fig. 3.19. The interaction of factors for surface roughness of surface A

The measurements (see Table 3.3) and visual observations indicate, that the surface quality of the sheet at the side of support is worse than at the side of the tool.

The experimental study suggests that the surface roughness of the sheet at the support side depends on many different factors, all of which are not covered in the current study. The quality of surface at the support side is influenced also by:

- Surface quality of the support if the blank is pressed in the forming process between support and the tool. Sheet in some extent copies the surface texture of the support. Although the support was made of soft material (softer than aluminum blank), it still left visible marks on the sheet surface.
- Microstructure and mechanical properties of the sheet material. If sheet metal is heavily deformed, particularly if it is coarse grained, it often develops a rough surface texture commonly known as "orange peel" (ASM, 1988). The effect was visible on most parts in the study.

Comparing the results of measurement of the surface roughness in ISF with and without support (see previous section), it may be seen that in case of forming without support the surface quality is better. At the same time, in later case, the minimum value of tool radius was 3 mm, i.e. smaller, and the range of p_z was the same. This can be explained with greater flexibility of material in forming process – in forming with support the material is pressed between the tool and the support, while in forming without support, material is at the forming area in contact only with the tool. So, plastically deformed zone is smaller, and material moves back when the tool continues its travel. It appears that in forming without support the surface quality is better, and it occurs at the cost of accuracy.

It is the task of engineer to decide the orientation of the part taking into account the visibility of the surfaces. For higher quality some extra polishing operations may be required.

An important parameter in metal forming is the force required for successful forming operation. It prescribes the selection forming tools and machines. One of the positive aspects of ISF is the fact, that the forming force does not depend on the size of the part. So, large parts can be made without the need for increase of stiffness of machine tool, i.e. no extra cost (if dimensions of working volume of the machine tool are sufficient).

In current study the force components in ISF were measured. As can be seen in Table 3.3, horizontal components are considerably lower than vertical component.

The force components measured in the experiment are shown in Fig. 3.20. The smaller peaks on the graph (see F_z) are emerging at the corners of rectangular toolpath, and the higher peaks at the step-down movement of the tool. In Fig. 3.20 only a fragment from the beginning of the force graph is presented. The peak forces of cycles gain certain stable level if the geometry is uniform, like on the experiments.

The force component values were saved in ASCII-file. The maximum values were extracted and analyzed using programs written in MATLAB environment.

As can be seen in Fig. 3.20, the force patterns in the *x* and *y* directions are not similar. This is due to sheet anisotropy and non-symmetric deformation mode. The obtained results are in agreement with the results given by Jadhav (Jadhav, 2004).

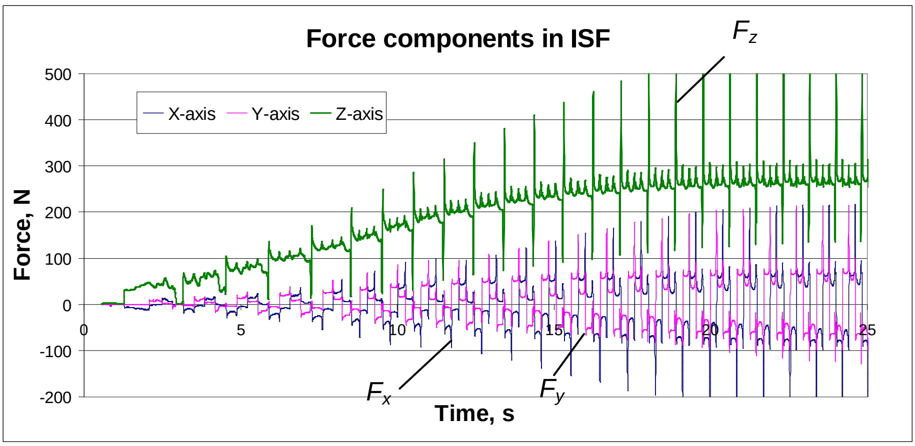


Fig. 3.20. Force components measured in experimental study (Pohlak, 2007 a)

The significant factors for maximum force component in *x*-axis direction are shown in Fig. 3.21. As can be seen, the wall angle (factor C on the chart) has the largest impact. It also has the largest impact on the maximum force component in *y*-axis direction (see Fig. 3.22). As can be seen in Figures 3.21 and 3.22, there is a difference in significant interactions.

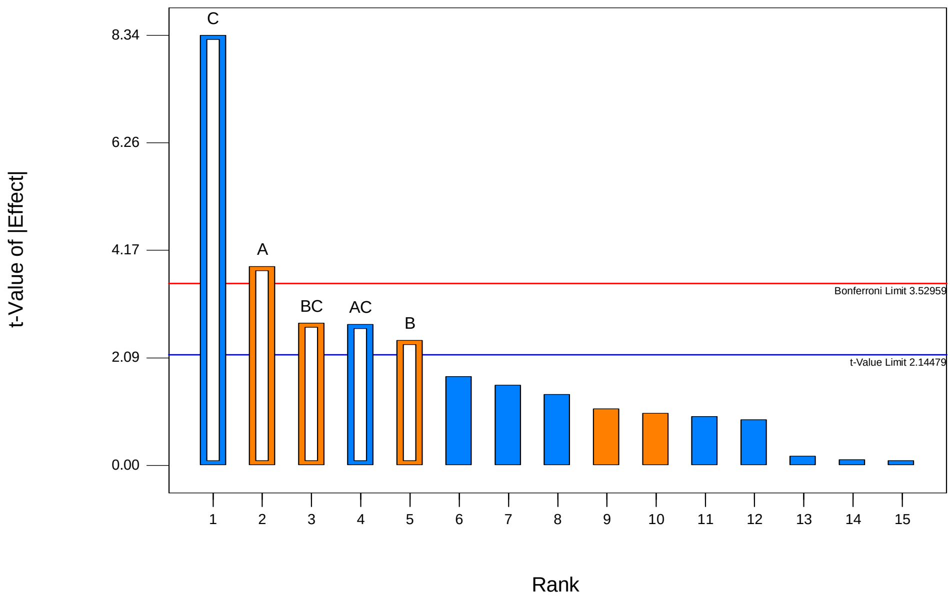


Fig. 3.21. The significant factors for force component in *x*-axis direction

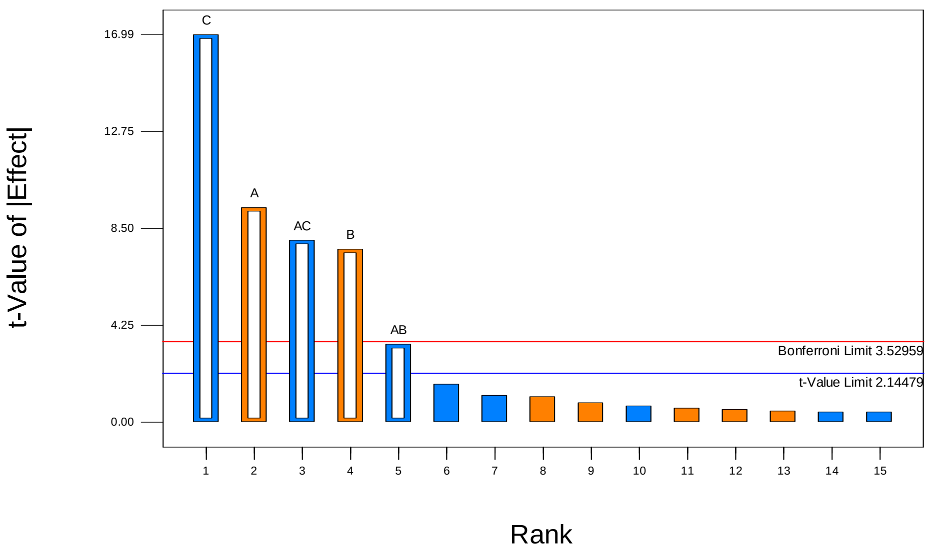


Fig. 3.22. The significant factors for force component in *y*-axis direction

The effect of interactions of p_z and α on force in *x*-axis direction is shown in Fig. 3.23. As can be seen, the maximum force value greatly depends on the parameters.

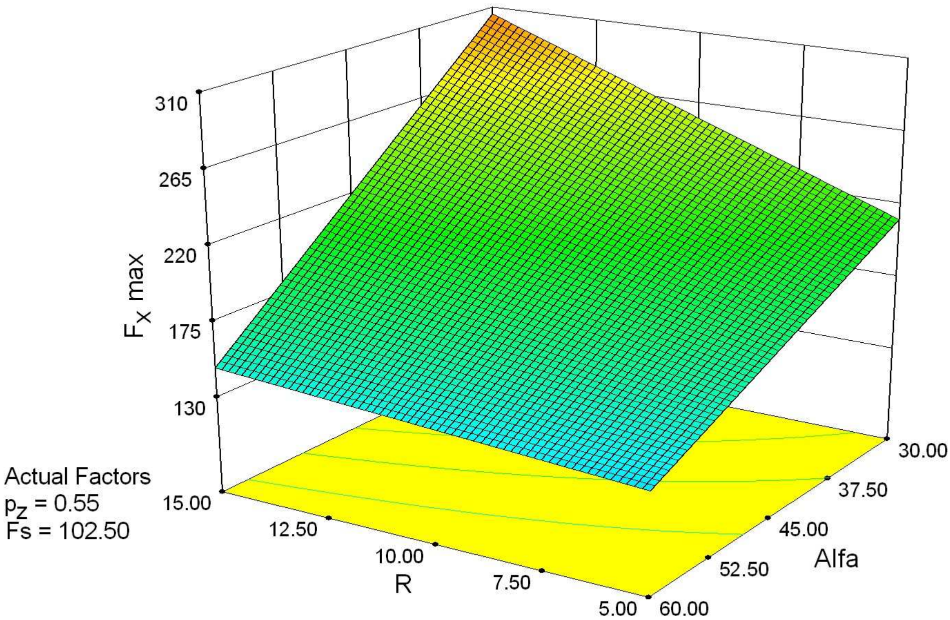


Fig. 3.23. The interaction of factors (force in *x*-axis direction)

The experiments indicated that vertical force component was several times higher than horizontal components. This situation is positive, because the horizontal components try to bend the tool, which is worse than compression that occurs due to vertical component.

The significant factors for maximum force component in *z*-axis direction are shown in Fig. 3.24. As can be seen, vertical step size (factor B on the chart) has the largest impact. Here the interactions appear to be insignificant.

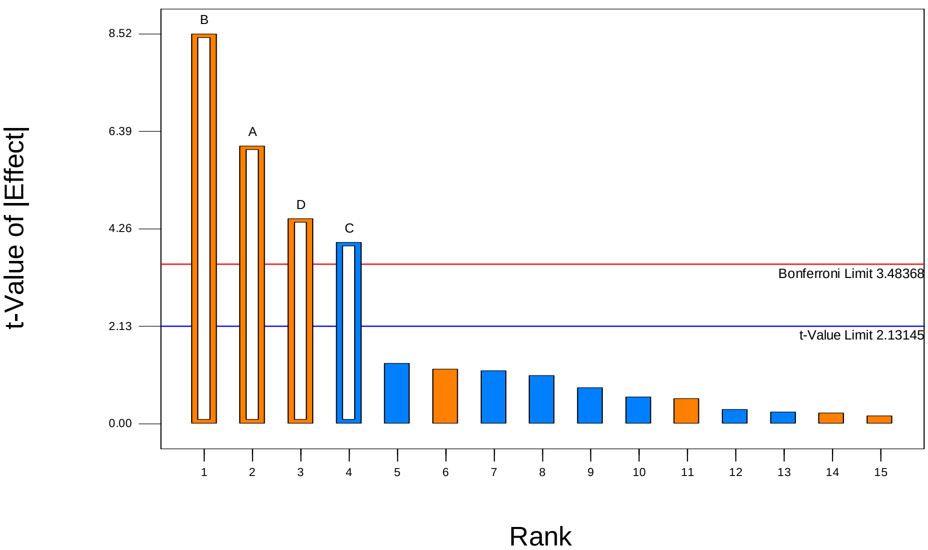


Fig. 3.24. The significant factors for force component in *z*-axis direction

Usually, depending on the toolpath, ISF process leaves a visible line (step-down line) on the surface of the part. The line may cause problems in several applications. In current study the influence of the factors on the step-down line was measured.

The significant factors for surface roughness parameter Ry across step-down line are shown in Fig. 3.25. It appeared that the most important factor is α. Other factors play significant role as well.

The same chart for surface roughness parameter Ra is in Fig. 3.26. Here, the most significant factor is p_z; also R and their interaction, is important.

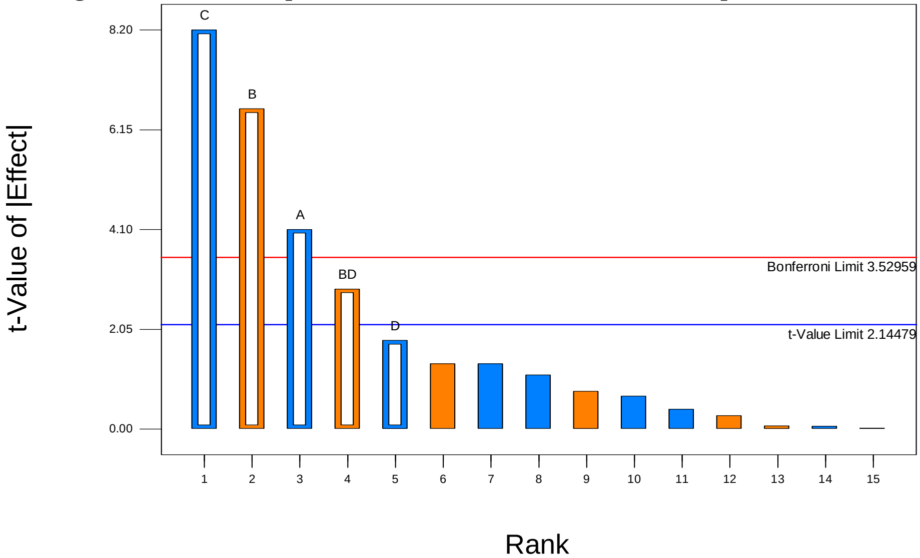


Fig. 3.25. The significant factors for Ry across step-down line

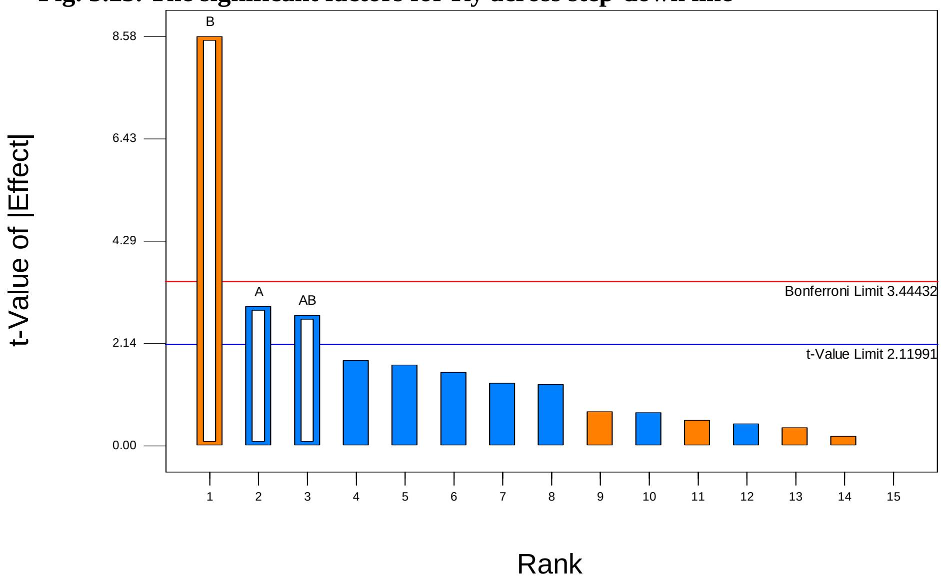


Fig. 3.26. The significant factors for Ra across step-down line

The diagram in Fig. 3.27 shows the influence of surface roughness Ra across the step-down line. The figure shows, that in the case of small tool vertical step, the roughness is not influenced by the tool radius. At higher levels of step size, the influence is considerable. So, one may conclude, that when designing the ISF process, selecting of tool radius and choosing step size needs to be considered together. It is especially important in view of processing time – the time depends directly on step size used in forming.

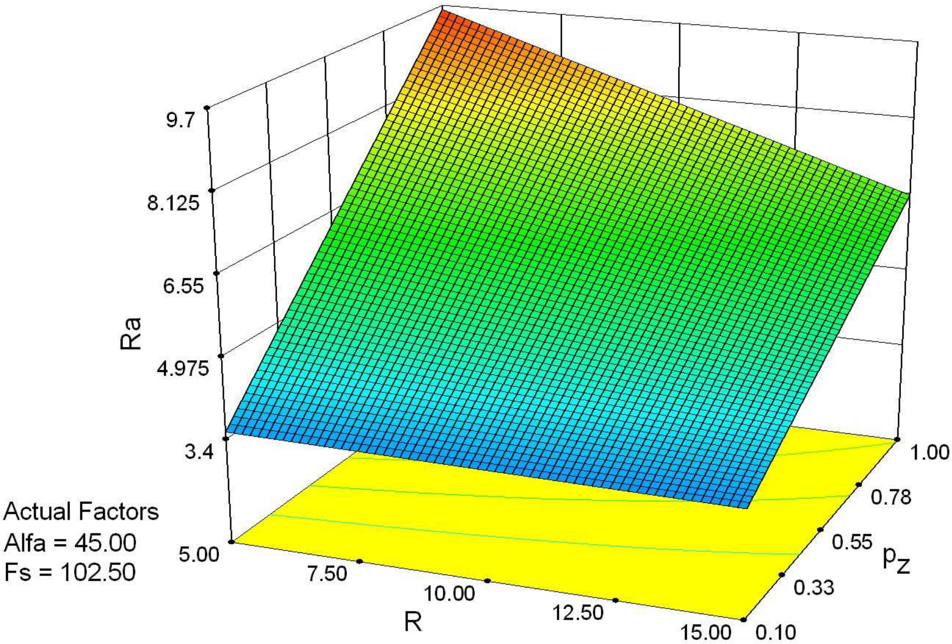


Fig. 3.27. The interaction of factors (Ra across step-down line)

3.3 Conclusions of the Chapter

1. There are two main variants of incremental forming, forming with support and forming without support. For both cases extensive experimental study, based on theory of design of experiments, was conducted. The material used in experiments was soft aluminum alloy.
2. In experimental study of ISF without support, the influence of tool radius, vertical step size and wall draft angle on wall thickness, flatness deviation, surface roughness and total form deviation was studied. The two level experimental design was used. The regression models for predicting the parameters were built. Based on experimental study, it was observed that:

- The majority of form deviations occurred due to deflection of unsupported surfaces, and can be avoided by using supports and backing plates.
- The form deviation was mainly influenced by vertical step size and wall draft angle. The influence of both parameters was significant.
- The sine law described the thinning effect with acceptable accuracy. It can be used for estimating the thickness of the wall in most cases.
- The surface roughness on tool side depends on all three factors: vertical step size, tool radius, and wall angle. In addition, lubricant and tool surface quality have the influence on the surface roughness.

3. In experimental study of ISF with support, the influence of tool radius, vertical step size, stretching force and wall draft angle on flatness deviation, surface roughness, forming force components and several characteristics of step-down line was studied. The two level experimental design was used. The regression models for predicting the parameters were built. Based on experimental study, it was observed that:
   - The flatness varied more than 10 times depending on selected parameter values. The surface flatness depended most on wall angle.
   - In most cases, the surface roughness was better on tool side. The surface quality was worsened by "orange peel" effect, affected by grain size of material. If the surface quality of the part is important, then the position of the part in forming must be taken into account.
   - The surface roughness was mostly influenced by step size and tool radius. So, if surfaces with better quality are needed, then the processing time increases (processing time depends directly on step size).
   - The forces in forming were relatively low, however the value of them changed in the process considerably. The high force peaks were observed when the tool was at the corners of the pyramid. Highest peaks in vertical force component values occurred when the tool made step-down action. The vertical force component was more than two times higher compared to the horizontal forces.
   - It was found that the horizontal force components depend most on wall draft angle, and the vertical force component depend most on vertical step size.
4. It can be concluded that forming with support allows achieving more accurate geometry, but it also adds some extra cost due to the need for preparing supports.

5. It was found, that the residual stresses caused by incremental forming can induce form deviations after cutting-out operations. So, heat treating, for example, annealing of the part after forming, may be required. However, the influence of residual stresses was not studied in the current thesis, and it needs further investigation in the future.

4 RECOMMENDATIONS FOR DESIGN OF PRODUCTS AND PROCESSES

In industrial implementations of ISF, it is important to know the limiting factors of the process. The limiting factors may be due to:

- Special features of ISF process (it is hard to form accurately shallow surfaces with large radius of curvature, and steep surfaces)
- The machine tool used (productivity, sheet material thickness to be formed, part size, etc.)
- The forming tool and the fixture (minimal curvature radius of surfaces, required surface quality, material to be formed, etc.)
- The material used (formability, spring-back, etc.) and other

In the following sections some recommendations and comments regarding these factors are given.

4.1 Considerations of Manufacturability

4.1.1 Forming Forces

It is essential to know the forces required for successful operation in forming process, especially for appropriate equipment selection.

In order to predict and avoid forming tool failure, the force required for incremental forming should be determined. In the literature some techniques for prevention of tool overload may be found. Ceretti et al. described a special tool holder with ability to compensate for too high loads (Ceretti, 2004). It is especially important if rigid metal support is used, and the gap between tool and support is kept small.

In order to analyze the forming loads, the forces were measured with the set-up shown in Fig. 4.1. It consisted of ISF fixture that was mounted on top of the piezoelectric load cell. The load cell was able to measure forces in 3 axis direction. Additionally, the measuring system included charge amplifiers, data acquisition cards and a PC. The sampling rate in force measurement was 50 Hz.

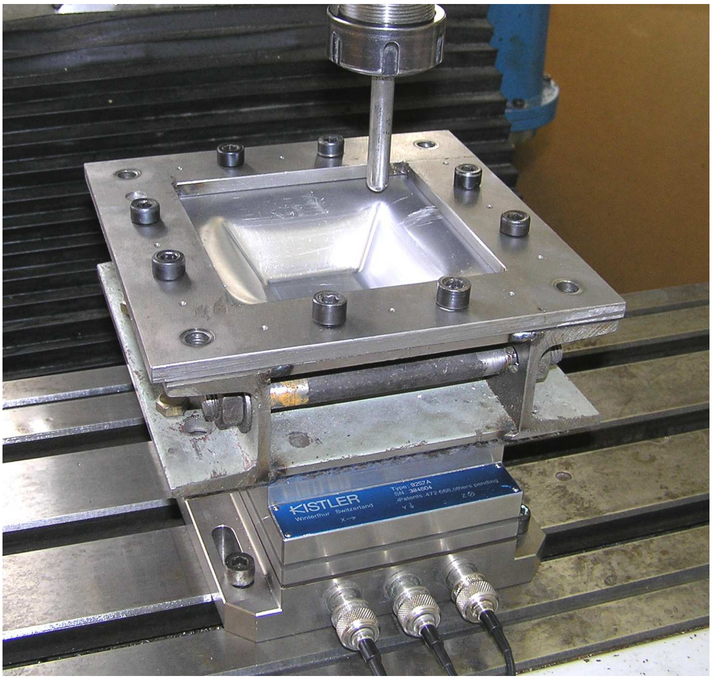


Fig. 4.1. Set-up for force measurement in ISF process on a NC machining centre (Pohlak, 2006 a)

The square pyramid shaped box was formed on CNC milling machine, and the force components were measured in *x*, *y* and *z* directions. Fig. 4.2 shows the force components measured in the experiment. It was concluded that the force diagrams are similar in positive and negative ISF.

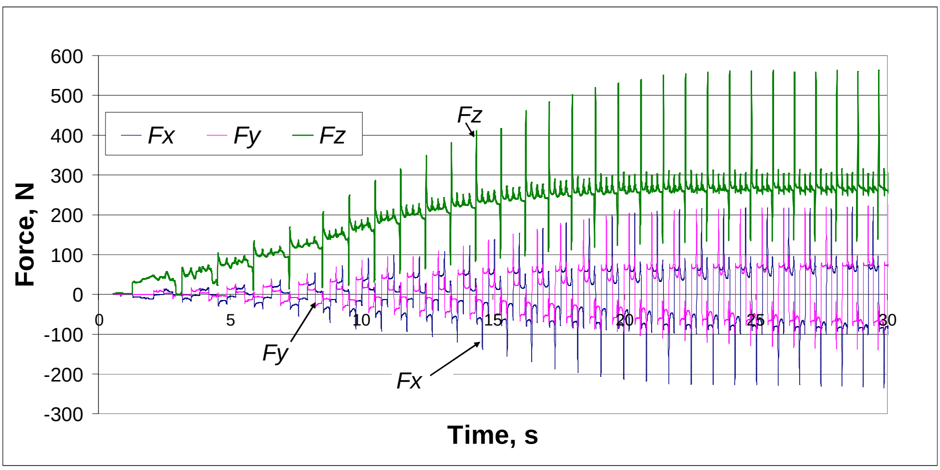


Fig. 4.2. Force components measured in experimental study (Pohlak, 2007 a)

As it can be seen in Fig. 4.2, the force patterns in the *x* and *y* directions are not equal, which is caused by sheet anisotropy and non-symmetric deformation mode. The obtained results are in agreement with the results given by Jadhav (Jadhav, 2004).

For more detailed analysis of forming forces, FEA was made. The finite element analysis model for simulation of incremental forming processes of sheet metal developed by the author is described in (Pohlak, 2004 a; Pohlak, 2004 b). In order to validate the FEA results, the reaction force data from calculation was compared with measured values. The force diagram obtained by use of FEA is shown in Fig. 4.3.

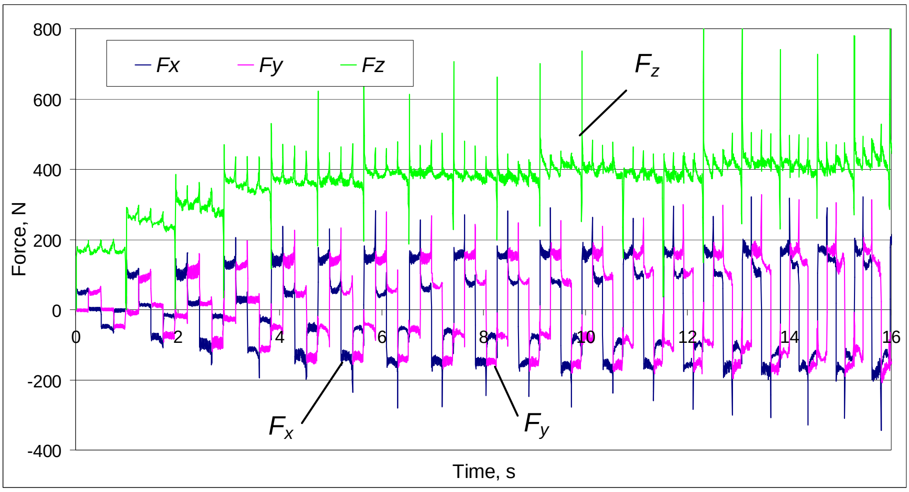


Fig. 4.3. Force components obtained by FEA (Pohlak, 2007 a)

The ISF process was modeled using FEA software LS-Dyna. The anisotropic yield criteria (Barlat) and exponential stress-strain approach were employed (Hallquist, 2006). The material parameters including the Lankford coefficients, the yield stresses and the stress-strain curve data were determined experimentally.

Note that the time scales in Fig. 4.2 and Fig. 4.3 are different, i.e. the comparison can be made considering the load curves; generally, peaks occur when the tool is in corner of the pyramid and higher peaks of F_z occur when the tool is making the vertical step downwards.

Comparison of Figs. 4.2 and Fig. 4.3 shows that the force patterns are in agreement. However, the calculated forces are higher than those measured experimentally. This fact may be caused by approximation used for describing strain-hardening behavior in the FEA model. Similarly, higher calculated forming limits compared to those obtained experimentally have been also observed, when simple exponential (Hollomon) strain-hardening relationship was adopted (Sing, 1997). In (Sing, 1997) the Voce approximation was suggested for copper and aluminum alloys. The current FEA model is planned to be improved by describing strain-hardening behavior of the material with multi-linear approximation.

If FEA model is improved, use of numerical simulation in everyday engineering work for estimating forming forces may be practical. In most cases, the simulation of full ISF process is extremely time consuming, but not in case where only the force values are need. In this case the simulation with the extreme parameter values (maximum p_z and R; minimum α, etc.) used in the process can be performed. The geometry of the part in the simulation may be more simple than real part and the simulation needs only to run until the forces reach stable level (process is stabilized). This way, prediction of the forming forces with reasonable calculation time is possible.

4.1.2 Lubrication

Lubrication appears to be an important factor in sheet metal forming. It reduces friction at the tool-workpiece interface and improves surface quality. Different lubrications are recommended for different materials and different forming processes (ASM, 2006). However, it appears that in ISF the magnitude of forming forces is not influenced by the composition of lubricant, but it is important that some sort of lubricant is used (Duflou, 2007 a). The similar conclusion has been reached by the author of the current thesis. However, local surface defects influence the formability in ISF (Jeswiet, 2005 a). Thus, if lubrication does not affect the forming forces, it probably affects the formability. The current experimental study proved, that if lubrication with poor properties is used, the material is scratched and small particles are rubbed out. It causes clearly visible lines on the surface. It is especially serious problem if harder materials (e.g. steel) are formed.

Fig. 4.4 shows the forming force components (note that z-axis component is scaled down 5x). It this experiment 1 mm thick aluminum sheet was formed with negative forming approach. The process started without any lubrication. As can be seen, the forces in horizontal plane (x-y plane) increase rapidly, while vertical force component increases at normal rate. The tool started to scratch the surface; bigger and bigger material particles separated from the sheet. At approximately 95 seconds from the start (see Fig. 4.4), the lubrication (mineral oil) was added. As can be seen, the force values drop considerably, and the process continues normally.

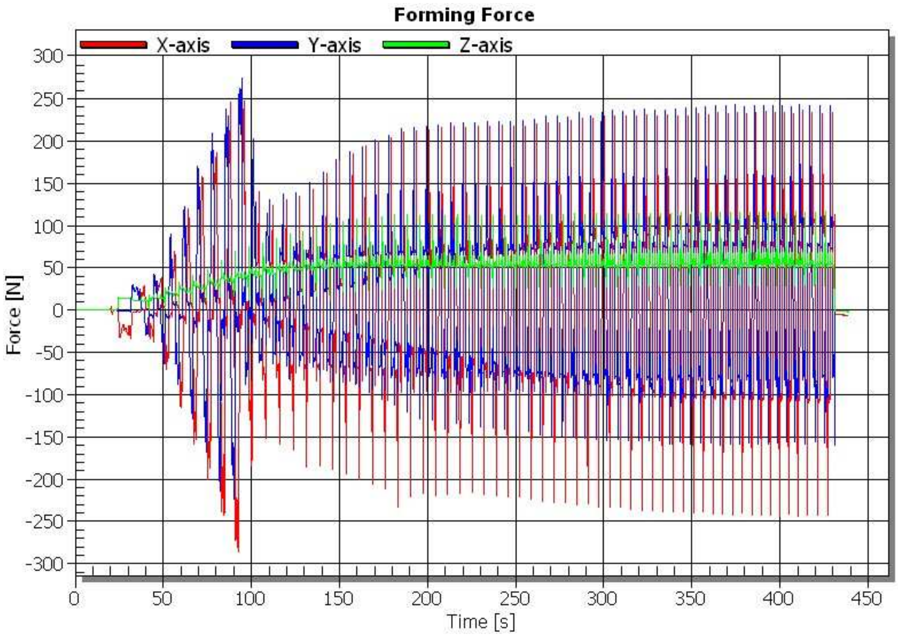


Fig. 4.4. The effect of lubrication on forming forces

The adhesive wear is considered to be the dominant wear mechanism (Duflou, 2007 a). As it has been experienced, the soft aluminum is able to wear hardened steel tool. So, the lubrication in ISF is important. However, the selection of proper lubricants for different materials needs further study.

4.1.3 General Technological Issues

Although ISF has some useful features, it has some serious drawbacks as well. The main drawbacks are the problems with making steep walls, and low accuracy induced by elastic spring-back. These topics are discussed below.

Problems with Steep Walls

In ISF the final thickness of the wall depends directly on the wall draft angle (denoted with α in Fig. 1.12 a)). If α is approaching 0°, the strain state is above forming limit curve and material will break (Pohlak, 2005). Generally, when using soft aluminum, walls with $\alpha > 30°$ can be produced without material failures. Although some researchers have reported achieving $\alpha = 0°$, it is too complicated to accomplish in everyday industrial practice. Thus, this is a serious limitation of ISF, which will exclude many possible applications.

Problems with Elastic Materials

Serious accuracy problems arise in case of processing elastic materials, e.g. stainless steel. Elastic springback effect may play important role, particularly in the situations where the gap between the tool and the support has been left too large or forming without support is performed. The effect of springback is shown in Fig. 4.5. This will appear especially after cut-out operations, when large relatively stiff edges are removed. In case of large parts, deviations will cumulate and may cause geometrical errors of several millimeters or more. Thus, thermal treatment for residual stress removal is required before cut-out operations.

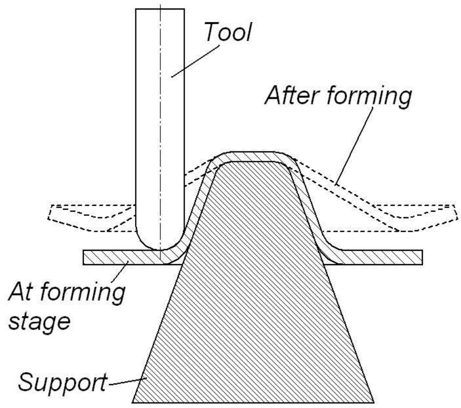


Fig. 4.5. Springback

The most important topic of studies in area of ISF is currently the compensation of springback.

Problems with Surfaces with Large Radius of Curvature

As mentioned before, problems with steep walls exist, but it appears that some accuracy problems with shallow surfaces with large radius of curvature occur as well. This is caused by elastic spring-back, discussed in previous section. In addition, smaller vertical tool step should be used to avoid visible forming lines on the surface. All those factors should be taken into account while planning production using ISF processes.

Gap Between the Tool and the Support

One practical question is how large gap between the forming tool and the support should be left. If it is too large, the deviation will be too large as well, but if it is too small, the sheet is pressed between the tool and the support, causing ironing effect (thinning occurs). As undeformed material is relatively stiff, the material is pressed out from the tool-support contact area (not enough room left for sheet thickness). As material cannot move back and down relative to tool motion (tool blocks the movement), and forward (thick and relatively stiff un-deformed material prevents it), it will move up causing surface deviation on upper surfaces and lifting the previously formed surfaces off the support (see Fig. 4.6).

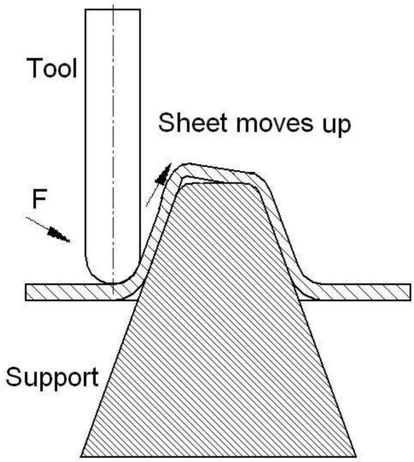


Fig. 4.6. Ironing effect

As a result, the formed object will be higher (stretched in vertical direction) than the support used in the forming process.

On one hand, if the tool moves too close to the support, ironing effect causes form deviations. On the other hand, if there is too much room left for the sheet, the part will not be accurate either. So, optimal offset should be used.

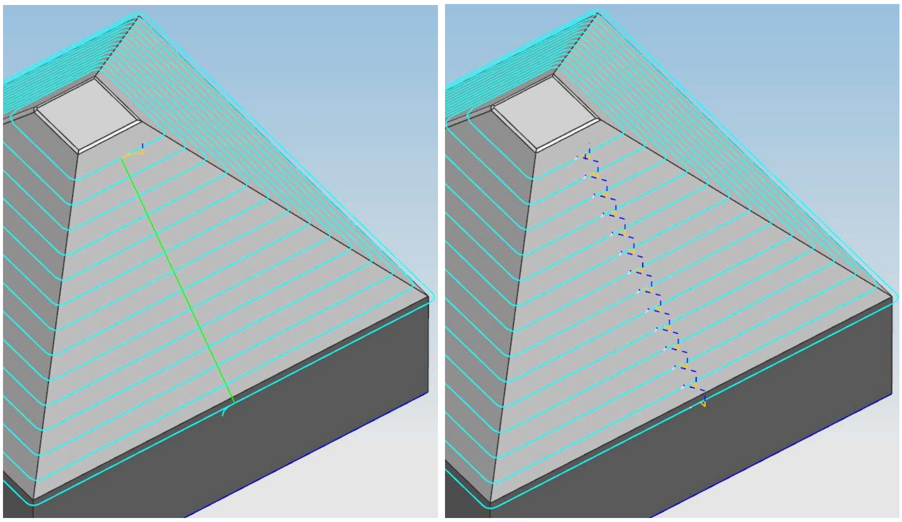
Ironing effect, as the author has discovered, may cause form deviations in range of several millimeters.

A good starting point in gap selection is the initial sheet thickness (Maki, 2006).

4.2 Toolpath Strategies

In ISF the selection of toolpath strategy is very important. The toolpaths are normally prepared using commercial CAM systems. Although, very many special CAM systems can be successfully used, most convenient are these systems that have good toolpath generation capabilities and in addition are integrated with CAD systems used for designing the parts. In this case the toolpaths can easily be up-dated after changes in part geometry. The studies conducted on the scope of the current thesis were performed using different CAM systems: Surfcam, Mastercam, ProEngineer and Unigraphics. The most suitable one turned out to be Unigraphics, thus majority of the latter work has been done using this system. It has excellent CAD-CAM integration and good capabilities of generating different types of toolpaths.

Generally the tool in ISF has to move more or less parallel to sheet blank, i.e. on *x-y* –plane or on horizontal plane (assuming that vertical machining centre is used). The forming begins from more stiff areas, i.e. near the highest part of support in positive forming or near sheet fixture in negative forming, and continues to lower stiffness areas. The tool can not move abruptly deeper (along tool axis), because the material will break. The vertical step must be relatively small, in order to achieve as even deformation of the workpiece as possible. The simplest toolpaths are shown in Fig. 4.7. All modern 3-axis CAM systems are able to generate toolpaths like these.

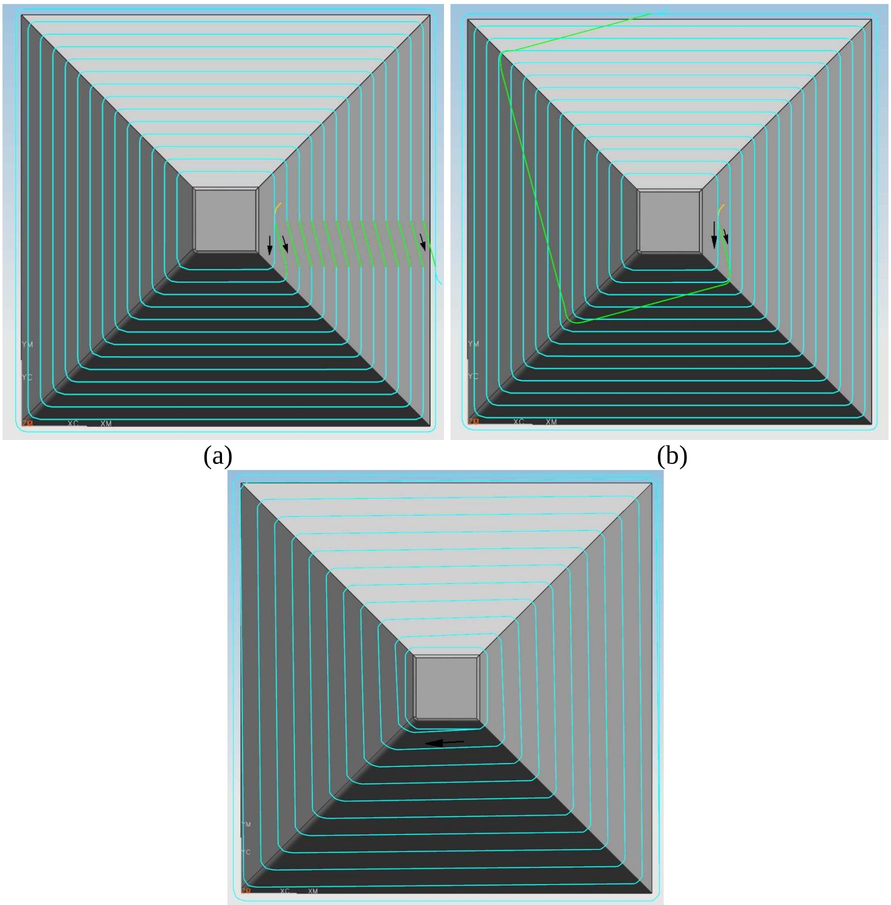


(a) (b)

Fig. 4.7. The simplest toolpaths used in ISF

In CAM systems the geometry is sliced horizontally into many layers with predefined thickness. Then, based on the contours of the slices, the toolpaths are prepared. The step from one layer to next can be performed in several ways. The simplest is by moving by straight line, like shown in Fig. 4.7 (a). Another possibility is shown in Fig. 4.7 (b), where the tool moves to the position of next section without moving down (same z-level), and then makes a step downwards. Both approaches produce a visible step-down line, which worsens the quality of the part considerably. The step-down lines were studied experimentally (see the chapter of experimental study in the current thesis).

To avoid or reduce the influence of step-down line, the spiral of helical toolpaths can be used. Some types of helical toolpaths are shown in Fig. 4.8. In Fig. 4.8 (a) the approach where the step-down is dispersed to bigger area is shown. The approach, depicted in Fig. 4.8 (b), is an enhanced version of the approach shown in Fig. 4.7 (a). Here the step-down line is spiral like, thus it is not so noticeable. The best approach is shown in Fig. 4.8 (c), where the toolpath is helical with constant smooth decline. However, the latter toolpath is not always applicable to more irregular shapes.



(a) (b)

(c)

Fig. 4.8. Different toolpaths with helical (spiral) approach

Another aspect is the turn-along effect of the workpiece. If the tool makes cycles only in one direction, the frictional forces shift the workpiece and cause form deviations. This can be avoided by use of similar toolpaths shown Fig. 4.7, but where the direction of tool is changed on each cycle. In this case, the problem of step-down line arises again.

When parts with complicated geometry are produced, the change in step down size is required in order to keep the production time in control and achieve optimal quality. At present, most commercial CAM systems do not provide the capability of changing the step size automatically for constant surface quality.

4.3 Optimization of Product and Process Parameters

In the preliminary phase of operation design, the main geometrical parameters of operations as length of the tool path (L), draft angle of the wall (α), number of technological passes (intermediate operations) and the wall thickness after processing (t) must be determined considering the geometry of the machined part.

Using the models that were prepared in experimental study (for more detailed description see (Pohlak, 2004 b)) a non-linear optimization problem can be formulated for design of the incremental forming operation. The optimization problem has been studied using MATLAB software system.

For given geometry of the part the objective is to find the control parameters of an operation (p_z, R and α), that give the minimum machining time (maximum productivity) (Küttner, 2004):

$$T = T(L, p_z, R, f, \alpha) \rightarrow \min, \tag{4.1}$$

and satisfy the constraints:

$$\begin{aligned}
&e_f\ (R, p_z, \alpha) \le [e_f],\\
&SR(R, p_z, \alpha) \le [SR],\\
&e_{fd}(R, p_z, \alpha) \le [e_{fd}],\\
&\alpha_{\min} \le \alpha \le \alpha_{\max},\\
&R_{\min} \le R \le R_{\max},\\
&p_{z\min} \le p_z \le p_{z\max},\\
&t(\alpha) \ge [t],\\
&f \le [f],
\end{aligned} \tag{4.2}$$

where f is the feed rate of the tool; p_z – vertical step size; R – tool radius; SR – roughness of processed surface; e_{fd} – form deviation of the part; e_f – flatness deviation of flat regions. Parameters in brackets, e.g. $[t]$, $[e_f]$ etc. represent maximum allowable values of corresponding parameters.

After the optimization the additional approximate or FEM deformation analysis must be made (post-processing phase).

In order to validate the plastic instability condition (Hill, 1952; Swift, 1952)

$$\frac{\partial \sigma_y}{\partial \bar{\varepsilon}^P} = \frac{\sigma_y}{Z} \tag{4.3}$$

in FEM analysis the post-processing variable "risk of necking" is introduced as

$$\psi = \begin{cases} e^{\bar{\psi}} - 1 & for \quad \bar{\psi} < 0 \\ 1 - e^{-\bar{\psi}} & for \quad \bar{\psi} \ge 0 \end{cases}, \tag{4.4}$$

where

$$\overline{\psi} = \frac{1}{Z} - \frac{\partial \sigma_y}{\partial \bar{\varepsilon}^P} \frac{1}{\sigma_y}, \tag{4.5}$$

and where σ_y is the yield limit:

$$\sigma_y = K\bar{\varepsilon}^n \tag{4.6}$$

and where $\bar{\varepsilon}^P$ is the effective plastic strain increment and

$$\bar{\varepsilon} = \frac{(1+R_a)}{(1+2R_a)} \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \frac{2R_a}{(1+R_a)} \varepsilon_1 \varepsilon_2}\ , \tag{4.7}$$

where ε_1 is the major strain and ε_2 is the minor strain; R_a is an average Lankford coefficient: $R_a = (r_0 + 2r_{45} + r_{90})/4$ (i.e. normal anisotropy is assumed). Lankford coefficients r_0, r_{45}, r_{90} measured along the rolling, diagonal and transverse directions of the sheet, respectively are defined as width to thickness strain increment ratios

$$r_\beta = \frac{\varepsilon_w}{\varepsilon_t},\ \beta \in \{0,45,90\}. \tag{4.8}$$

In (4.6) n is a strain hardening exponent, K is a strength coefficient.

If Z is a function of principal stress ratio $\rho = \sigma_2 / \sigma_1$, where σ_1 is the major stress and σ_2 is the minor stress, then $Z = Z_{Hill}$ in the case of the negative strain increments ratio (localized necking) and $Z = Z_{Swift}$ otherwise (diffuse necking). The value of the variable ψ ("risk of necking") at an integration point indicates how far a point is from necking:

$-1 < \psi < 0$, elastic or stable plastic deformation,

$0 \le \psi < 1$, unsafe flow.

An explicit expression of the function $Z = Z_{Hill}$ (or $Z = Z_{Swift}$) depends on particular yield criterion considered.

The parameters K, n, and R_a are determined experimentally from mechanical tests. Note, that the necking conditions, considered above, describe the metal sheet formability more adequately in the case of large vertical step size p_z (near to conventional forming). In the case of the small vertical step size p_z (real incremental forming) the safe zone is described with considerable reserve. Thus, the safe zone is still safe, but such an approach may give a quite robust results.

In order to describe the sheet metal formability in incremental forming more accurately, the criteria that considers the effect of the deformation history of process parameters is needed. Such type of criteria are the ductile fracture criteria. The forming limit of sheet metal is determined conventionally by the initiation of localized necking. Fracture occurs in the latter stage of localization, which initiates in the localized region.

Based on experimental results obtained in the current study, it can be concluded that in plane strain condition fracture strain can be used as an estimate for limit strain.

The influence of the parameters p_z and α on the solution of optimization problem posed above appears to be the most significant. The draft angle is subjected to strict constraints defined by the geometry of the part. The details concerning the optimization problem considered can be found in (Küttner, 2004; Pohlak, 2004 b; Pohlak, 2005).

4.4 Economical Considerations

Important aspect in implementation of the technology is the cost. In case of ISF, the cost of setting up the production is rather low (assuming the machine tool and the ISF fixture are available). It consists of costs associated with CAD/CAM work, material of support, machining of support, relatively slow production process, etc. On the other had, if traditional forming processes, like deep drawing, are used, the costs are associated with design of the tools, CAD/CAM work, material of the tools, machining, manual finishing and adjusting of the tools, etc. The design and manufacture of the tools are usually time consuming, but the production of the parts is fast.

The diagram with the comparison of costs vs. batch size in ISF and deep drawing, is shown in Fig. 4.9. The analysis was made for part with the dimensions of ca 800x400x200 mm (Lamminen, 2003). In the diagram, two separate ISF cases are presented, where different processing parameters are used. The cases are somewhat like worst and best case scenarios. It can be seen, that ISF technology is economically feasible if batch sizes are lower than 200-1000 parts. Usually, it is recommended to use ISF if batch size is less than 500 pieces (Lamminen, 2005; ASM, 2006). It is worth noting that, the forming costs in ISF strongly depends on the geometry and material of the part (ASM, 2006). In the current comparison moderate complexity of the part is assumed, i.e. part can easily be produced with ISF.

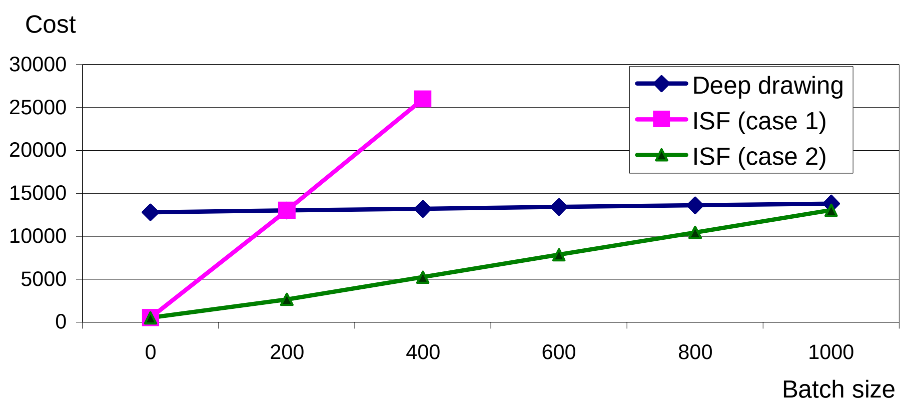


Fig. 4.9. Cost comparison of ISF and deep drawing (Lamminen, 2003; ASM, 2006)

If dimensions of the part are large and quality requirements are high, the processing using ISF takes long time, e.g. a part similar to car bonnet took >10 hours (Asnafi, 2003). It can be concluded, that if few parts are needed (i.e. prototyping) then ISF can be the economical choice.

4.5 Applications – Case Studies

The best method for investigating the implementation problems is by trying to use the technology for producing parts for real industrial cases. Below, some case studies made with different types of ISF are described.

4.5.1 Cooker

The ISF technology was used to produce casing for the cooker. It was designed within international student project, by Andri Laidre (Tallinn University of Technology) and Triin Voss (Estonian Academy of Arts) (Jammers, 2006).

The casing was made of 1 mm thick aluminum sheet. The dimensions of formed part were 550x300x20 mm. The ISF was chosen for producing the part, because it was the cheapest and fastest method available. The designers and the author of the thesis made cooperation to achieve the best possible outcome.

As it was noted in the experimental study before, the side of the workpiece where the tool moves, will have better quality. So, it was decided to form the part such a way that the tool is on the visible side of the part. It means that the positive forming (forming with support) had to be used, but the sheet fixture for such a large part was not available. A simple solution was found: the edges of the sheet were left unfixed, the sheet was fixed from the highest areas using four screws (see Fig. 4.10). If screw holes were not allowed to be drilled, then this solution could not be used. The support was machined out of MDF plate on the same milling machine as the part was later formed. It was easy to fasten screws into MDF plate, as the material is relatively soft. The support used in the project is shown in Fig. 4.11.

Fig. 4.10. Forming of the cooker casing in CNC milling machine

Fig. 4.11. Support for producing casing of the cooker

Slightly larger blank of the sheet was used than the overall dimensions of the final part, because the edges were free at the process. As it was observed, when forming near the free edges, the wrinkling may occur.

It is worth to mention that removing the redundant material caused some difficulties, because laser cutter was not available, and mechanical cutting caused due to softness of the material some distortions.

Due to operator mistake, it was also observed that if gap between the tool and the support is too small, then ironing effect occurs. It means, that the tool presses the sheet against the support causing thinning, so the area of the sheet is increasing. This induces low form accuracy.

The part was modeled using SolidWorks (developed by SolidWorks Corporation). The toolpaths for CNC were prepared using Unigraphics (developed by UGS Corp.).

The tool diameter was 10 mm, step size 0.15 mm. In the process mineral oil was used to lubricate the tool-sheet interface. The preparing of support took 2.5 hours. The forming process took about 2 hours.

The finished kitchen cooker prototype is shown in Fig. 4.12.

Fig. 4.12. Assembled prototype kitchen cooker (Jammers, 2006)

Lessons Learned

- Parts can be formed with ISF without special tooling or fixtures. Only support, made of soft material, is enough.
- Parts can be formed using different types (positive or negative forming) or set-ups of ISF. The proper selection of the set-up is crucial.
- Clearance between tool and the support is very important, as it affects the accuracy and appearance of the product significantly.
- The proper design of all operations, including cut-out operations, needs to be considered from the beginning.
- The production of sheet metal prototype using ISF is cheap, fast and relatively easy even if only general purpose workshop machine tools (CNC milling machine) are available.

4.5.2 Ashtray

For studying the nature of negative forming (forming without the support), the sea shell shaped ashtray was produced. The material used for the project was 0.5 mm thick stainless steel AISI 304. For the project no special shape fixture or back-up plate was used, it was produced in square shaped negative forming fixture, described in the chapter about experimental study.

The part was modeled using Pro/ENGINEER. The toolpaths for CNC were prepared using SURFCAM.

The ashtray, produced in current project, is shown in Fig. 4.13. As can be seen from the images, the forming lines produced by the tool are clearly visible. It means that much smaller step has to be used. After forming, it was tried to improve the surface and remove the stair-stepping by re-forming using different toolpath strategy (zig-zag). However, the improvement in surface quality was not achieved. The reason for this could be the fact, that the re-forming tool paths were too near to the toolpaths from the first forming step and therefore, the sheet was not deformed plastically. Thus, stair-stepping from the first stage was remaining.

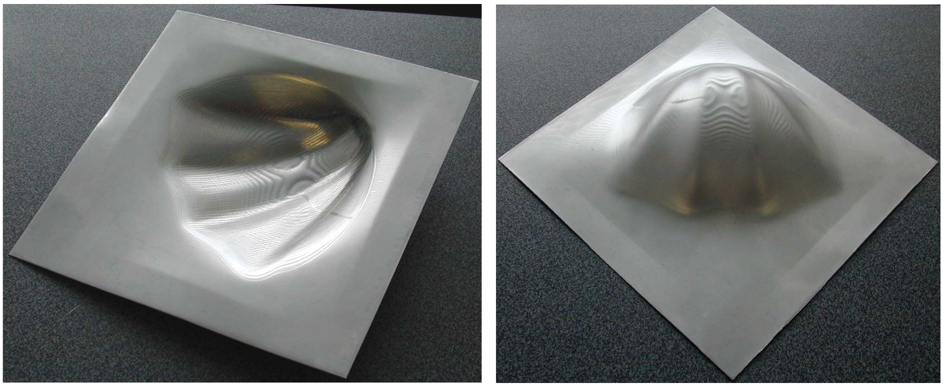


Fig. 4.13. Stainless steel ashtray

In the project the tool radius was 2.5 mm, vertical step size 0.15 mm. In the process mineral oil was used to lubricate the tool-sheet interface. The forming process took about 30 minutes.

Lessons Learned

- Step-down line is especially well visible in case of materials that are elastic and hard to form, like stainless steel.
- If a part is formed with too large vertical step, then re-forming to achieve better quality with smaller step size or different strategy does not improve the quality.
- Some people (in our case art designers) like the shapes with large stair-stepping, i.e. large vertical step size is used.
- Excessive bending and springback may cause problems if materials that are elastic and hard to form are used.
- Very small vertical step (even less than 0.1 mm) has to be used in case of smooth shallow surfaces.
- If stainless steel is formed, the contact pressures are much greater compared to forming of aluminum. So, better, and possibly different type of lubricant is needed.

4.5.3 Skin Component for PC Mouse

The upper part of computer mouse was produced as reverse engineering project. A mouse was scanned using laser scanner, the geometry was modified in CAD system, and then modified mouse part was produced using ISF technology. The parts were made of aluminum with 1 mm thickness and stainless steel (AISI 304) with 0.5 mm thickness.

Both, negative and positive forming, were tested for producing of the part (see Fig. 4.14). The negative forming is easier to implement, but in this case, a problem with the highest area of the part emerged. Due to the smooth geometry and deformation built-up, a small dimple occurred (see Fig. 4.14 (b)). It was especially problematic with stainless steel workpiece. Positive forming produced better results.

For positive forming, the support was made of NECURON® modeling plastic. The sheet fixture is described in chapter of experimental study of forming with support.

In the project the tool radius was 2.5 mm, vertical step size 0.2 mm. In the process mineral oil was used to lubricate the tool-sheet interface. The forming process took about 30 minutes.

The part was modeled using Pro/ENGINEER. The toolpaths for CNC were prepared using SURFCAM.

(a) (b)

Fig. 4.14. Mouse part: (a) produced by positive forming; (b) produced by negative forming

Lessons Learned

- Due to manufacturing limitations (mainly formability), it is important to consider the limitation early in design stage.
- The cut-out operations need to be considered more seriously in real life projects. Without 5-axis laser cutter, it is difficult to remove the excess of material.

4.5.4 Spoon

A tea spoon was produced using the negative forming approach. It was made of half millimeter thick stainless steel (AISI 304) sheet. The spoon was cut-out by milling after the forming operation using the same milling machine. The spoon after the forming operation and before cut-out is shown in Fig. 4.15.

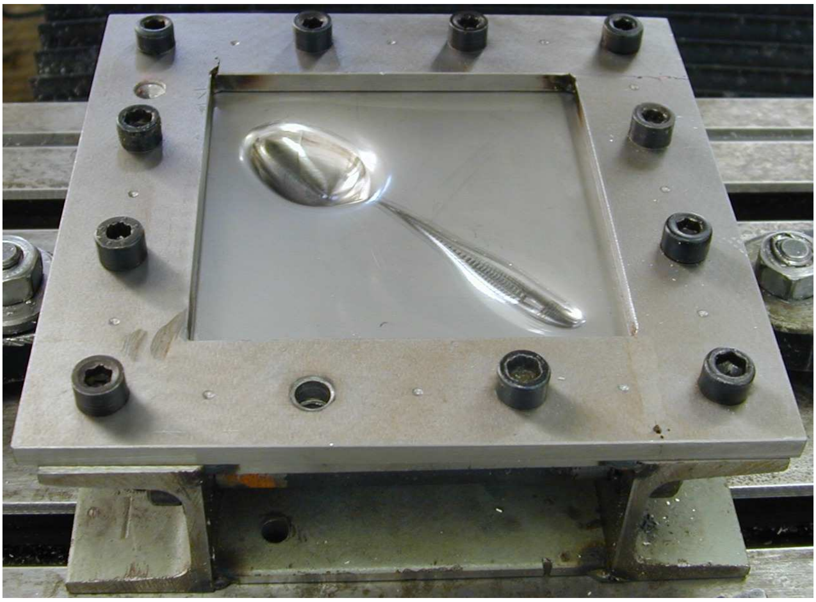


Fig. 4.15. Spoon before cut-out operations

The spoon in final form is shown in Fig. 4.16. As can be seen from the figure, lines drawn by the tool are clearly visible. The second problem is low form accuracy. This is caused mainly by high springback of the material.

In the project the tool radius was 2.5 mm, vertical step size 0.075 mm. In the process mineral oil was used to lubricate the tool-sheet interface. The forming process took about one hour.

Fig. 4.16. The spoon after finishing operations

The spoon was originally modeled by Mr. Annes Sutt using Rhino (from Robert McNeel & Associates), and later prepared for manufacture using Pro/ENGINEER. The toolpaths for CNC were prepared using SURFCAM.

Lessons Learned

- Springback in forming of elastic metals, like stainless steel is very high. Without some kind of error compensation the accuracy of geometry could be unacceptable.
- If good appearance is required, then considerable amount of manual finishing is needed.

4.5.5 Demonstration Parts

Some more general demonstration parts were made using the positive incremental forming approach. One of them was a motorbike component, and the other one the outer shell of hair drier (shown in Fig. 4.17 and 4.18 respectively). Although the parts were not used in real conditions, the case still shows potential applications of the process. The parts were presented on the largest Estonian industrial engineering related trade show as an example of possibilities of new flexible sheet forming methods.

In the projects 1 mm thick aluminum sheet was used. The radius of the tool was 5 mm, vertical step size was depending on the geometry different, ranging from 0.05 to 0.25 mm. Mineral oil was used to lubricate the tool-sheet interface. The duration of ISF process was approximately 2 hours for each part. The milling of the supports lasted one hour for each.

Fig. 4.17. Motorcycle component

Fig. 4.18. Hair drier component

The support for motorcycle component forming is shown in Fig. 4.19. It was made of modeling plastic NECURON®. Because of very good workability, the material allowed to use high feed rates and cutting speed. At the same time, the material was strong enough for supporting the sheet in forming.

The part was modeled using SolidWorks, and the toolpaths for CNC were prepared using Unigraphics.

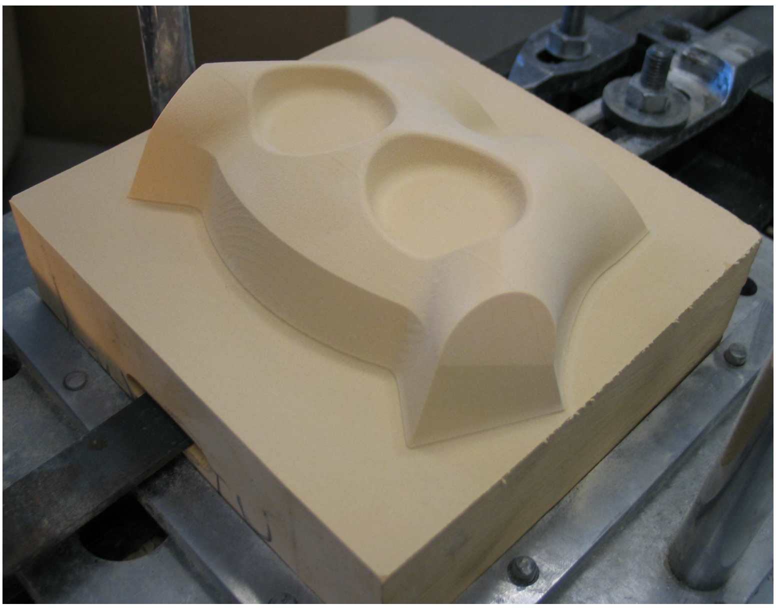


Fig. 4.19. Support for forming of motorcycle component

Lessons Learned

- ISF with support allows to manufacture parts with complicated geometry.
- To achieve acceptable surface finish on smooth shallow (large radius) surfaces, additional manual finishing may be needed.
- Supports made of soft materials (can be deformed even with finger nails) are able to withstand production of ten or more parts.

4.6 Conclusions of the Chapter

1. The successful implementation of ISF technology depends on overcoming the limitations of the process. The most serious aspects that prevent the wider use of the technology are low accuracy and productivity. In addition, a very serious drawback is the thinning of the sheet in forming.
2. Forming forces in ISF do not depend on the part size. The contact region of the tool and the sheet is small, so the forces are also relatively low. Therefore, relatively large parts can be manufactured on low cost machine tools.
3. FEA can be successfully used for estimating forming forces in ISF. To obtain forces by numerical simulation, simple models can be used, and only the fraction of the tool movement has to be calculated.
4. The toolpath strategies are important in respect to productivity, accuracy, surface quality and formability. General purpose commercial CAM systems can successfully be used for toolpath preparation in ISF. However, all systems have some limitations. To achieve the best quality, special CAM systems have to be programmed, that include databases with different materials' formability. The ideal system must include springback compensation capabilities.
5. Several case studies were conducted in order to investigate the application of the ISF technology for producing prototypes. It was learnt that, when forming with support, the support may be made of relatively soft, well workable material. The cut-out operations after forming caused some problems. It needs to be considered from the beginning of the process design. The most important conclusion is that sheet metal prototypes can be made using ISF in universal CNC milling machine fast and with low costs.

5 CONCLUSIONS

The main conclusions of the current thesis are as follows:

1. In the current study the incremental sheet forming with and without support has been studied in general purpose vertical CNC machining centre. Compared with traditional sheet forming processes, i.e. deep drawing, the incremental forming is economically feasible for producing prototypes and for small series production (batch size less than 500).
2. Analytical models for estimating forming forces have been studied. The Iseki's theoretical model for describing ISF process has been improved by introducing the influence of plastic anisotropy.
3. Numerical analyses of the forming process using implicit and explicit FEA programs have been made. Good correlation between the results of numerical and experimental investigation has been found. Generally, the simulation of the ISF process is complicated and time consuming. It was found that FEA can successfully be used for forming force prediction with simplified model.
4. The experimental investigations of the influence of process and product parameters were performed. Some of the indicators that are important for product and process design, e.g. surface roughness, can be studied only experimentally. As a result of the study, the models for estimation of most important process indicators in ISF have been determined. The parameters investigated in experimental study (both, forming with and without support) are as follows:
   - Radius of forming tool
   - Vertical step size of the tool
   - Wall draft angle
   - Stretching force (in ISF with support)

   The process indicators for which models were built are forming forces, sheet thickness, surface roughness, form deviation, flatness, characteristics of step-down line, etc.
5. From experiments it can be concluded that forming with support allows achieving more accurate geometry, but it also adds some extra cost due to the need for preparing supports.
6. It was found, that the residual stresses, caused by incremental forming, can induce form deviations after cutting-out operations. So, heat treating, for example, annealing of the part after forming, may be required.
7. Recommendations for product and process design and implementation were developed. Several case studies of forming real part prototypes were described. It was learnt that, when forming with support, the support may be made using relatively soft, well workable material. The cut-out operations after forming caused some problems. They need to be considered from the beginning of

the process design. The most important conclusion is that sheet metal prototypes can be made using ISF in universal CNC milling machine fast and with low costs.

8. The successful implementation of ISF technology depends on overcoming the limitations of the process. The most serious aspects that prevent the wider use of the technology are low accuracy and productivity. In addition, a very serious drawback is the thinning of the sheet in forming.

The ISF technology is in developing stage, many aspects have not been investigated, yet. The most important topics for future research are as follows:

1. Error compensation for removing deviations induced by springback
2. Specialized ISF toolpath strategies and software systems with built in error compensation mechanism
3. Toolpath strategies and software implementations for ISF with two industrial robots (forming with moving support)
4. The influence of residual stresses after cut-out operations
5. The integration of ISF technology into multi stage production system

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KOKKUVÕTE

Kaasaegses maailmas valitseb trend, et pakutavate kaupade nomenklatuur järjest kasvab. Toodete projekteerimisel arvestatakse järjest enam klientide erinevate vajaduste ja eelistustega. Üldine suund on üleminek tootmisele, kus toode valmistatakse konkreetse kliendi personaalseid eelistusi arvestades. Samal ajal ei tohi langeda toote kvaliteet ja eksisteerib tugev hinnasurve, mis ei lase tootjatel küsida toodete eest senisest kõrgemat hinda. Tänapäeval kasutatakse lehtmetallist detaile väga laialdaselt kõigis valdkondades. Lehtmaterjali kasutamise laienemise peamiseks piirajaks on tehnoloogilised piirangud – plastmaterjalidest survevalu teel valmistades võib valmistada oluliselt keerukama geomeetriaga detaile. Samas on plastide tooraine hinnad viimastel aastatel kasvanud. Lehtmaterjalist toodete valmistamiseks traditsiooniliste tehnoloogiatega on tarvis tööriistu, millede valmistamine on kulukas ja aeganõudev. Viimasel kümnendil on kasutusele võetud uus paindlik lehtmaterjalide vormimistehnoloogia – sammvormimine. See baseerub kihttöötlusel, kus toote geomeetria kujundatakse kihthaaval samm-sammult lehte vormides. Kasutatakse lihtsat sfäärilise otsaga tööriista, mida liigutatakse programmjuhtimisega tööpingis mööda keerukat töörada. Protsessis võib kasutada universaalset programmjuhtimisega freespinki. Leht kinnitatakse servadest spetsiaalsesse lehehoidjasse. Detaili vormitakse horisontaalselt (eeldusel, et kasutatakse vertikaalset tööpinki) ristlõige haaval, alustades jäigemast piirkonnast minnes sammhaaval edasi vähemjäigema piirkonna suunas. Iga ristlõike vormimise järel astub tööriist sammu alla ning asub töötlema järgmist ristlõiget. Tööpõhimõttelt võib eristada kahte sammvormimise tüüpi: toega ja ilma toeta vormimine. Esimesel juhul toimub vormimine, kasutades stantsimise termineid, matriitsi poolelt; teisel juhul templi poolelt. Esimesel juhul tuleb kasutada keerukamat, liikuvat lehe hoidjat ning spetsiaalset detaili kujuga tuge.

Käesolev doktoritöö keskendub lehtmaterjalide sammvormimise tehnoloogia uurimisele. Töö eesmärgiks on meetodite ja tehnikate arendamine sammvormimise tehnoloogia rakendamiseks. Käsitletakse muuhulgas ka toodete ja protsesside projekteerimisega seotud teemasid. Eesmärgi saavutamiseks on vaja lahendada alljärgnevad ülesanded:

- paindlike lehtmaterjali vormimistehnoloogiate ülevaate loomine;
- sammvormimise protsessi mehaanika uurimine kasutades teoreetilist ja numbrilist analüüsi;
- protsessi eksperimentaalne uurimine – toodete oluliste parameetrite mõju uurimine toote kvalitatiivsetele näitajatele;
- toodete ja protsesside projekteerimist hõlbustavate meetodite väljatöötamine;
- sammvormimise protsessi parandamine (täpsuse suurendamine, protsessi optimeerimine).

Töö sissejuhatavas osas on tehtud ülevaade lehtmetallist prototüüpide ja väikeseeriatoodete valmistamise meetoditest. Toodud on ka kirjeldatud meetodite eelised ning puudused.

Teoreetilise ja numbrilise analüüsi osas on täiustatud Iseki sammvormimise jõudude mudelit, lisades plastset anisotroopiat arvestava osa. Teoreetilises osas käsitletakse veel vormimise piirdiagrammide kasutamist ning ettevalmistamist sammvormimise tarbeks. Töö numbrilise analüüsi osas on uuritud vormimise protsessi mehaanikat kasutades lõplike elementide meetodit. Selleks viidi läbi arvutused staatika ning dünaamika analüüsi programmiga. Analüüsil kasutati koorikelemente, elastseid-plastseid materjalimudeleid ning kontaktiarvutust. Uuriti nii toega, kui ka toeta sammvormimise skeemi. Mudelite adekvaatsuse hindamiseks valmistati samade parameetritega reaalsed tooted ning võrreldi simulatsiooni tulemustega. Võrdlusel kasutati deformatsioone ja seinapaksust. Selgus, et täpsemad mudelid võimaldasid modelleerida rahuldava täpsusega seina õhenemist. Deformatsioonid erinesid reaalse detaili deformatsioonidest detaili eri osades piirides -0,8 kuni +0,74 mm (detaili gabariitmõõtmed olid 110x110x20 mm). Piiranguks simulatsioonide kasutamisel on nende pikk kestus – isegi väga lihtsa detaili vormimise simulatsiooniks kulus üle 24 tunni kaasaegsel personaalarvutil. Reaalsete detailide puhul pole kogu vormimise protsessi simulatsiooni kasutamine seega otstarbekas. Samas on võimalik edukalt kasutada lõplike elementide meetodit vormimisjõudude modelleerimiseks. Sel juhul pole tervet protsessi vaja arvutada, piisab "raskemate" parameetrite väärtustega simulatsioonist lihtsustatud mudeliga.

Doktoritöö kõige mahukam osa käsitleb sammvormimise eksperimentaalset osa. Siin on kirjeldatud uurimistööd, mille raames vormiti erinevate parameetritega püramiidikujulisi katsekehi nii toega, kui ka toeta sammvormimise tehnoloogiat kasutades. Materjaliks oli 1 mm paksune alumiiniumi leht. Eksperimentide tulemusel koostati mudelid tähtsamate toote ja protsessi parameetrite mõju hindamiseks väljundparameetritele. Parameetrid, mille mõju uuriti olid tööriista raadius, vertikaalne samm, seina kaldenurk ning toega vormimise puhul ka lehe toelevenitamise jõud. Väljundparameetriteks olid pinnakaredus, seinapaksus, kujuhälve, tasapinnalisus ja vormimisjõud.

Käesolevas doktoritöös leidsid kajastamist sammvormimise kasutuselevõtuga seotud küsimused. Toodi ära hulk soovitusi tehnoloogilistes küsimustes, sh. määrimise mõju protsessile, tööradade loomisega seonduv, protsessi parameetrite optimeerimise võimalused. Kasutuselevõtu illustreerimiseks kirjeldati terve rea reaalselt valmistatud detailide vormimisega seotud aspekte.

Töö põhilised järeldused on toodud alljärgnevalt.

1. Sammvormimine on majanduslikult otstarbekas juhul, kui partii on väike (alla 500 detaili).
2. Töös käsitleti analüütilist jõudude mudelit. Olemasolevat Iseki mudelit täiustati selliselt, et see arvestaks ka plastse anisotroopia mõju.

3. Viidi läbi sammvormimise simulatsioonid kasutades kahte erinevat lõplike elementide meetodil põhinevat tarkvarasüsteemi. Simulatsioon on keerukas ja aeganõudev. Seda saab edukalt kasutada vormimisjõudude hindamiseks.
4. Töö käigus viidi läbi sammvormimise (nii toega, kui ilma) katseline uurimine. Analüüsiti olulisemate parameetrite (tööriista raadius, vertikaalne samm, seina kaldenurk ja toele venitamise jõud) mõju toote omadustele (pinnakaredus, seinapaksus, kujuhälve, tasapinnalisus, vormimisjõud). Omaduste hindamiseks loodi mudelid.
5. Katseline uurimine näitas, et toega sammvormimine võimaldab saavutada toodete paremat täpsust, ehkki ka lisab mõnevõrra töömahtu, mis on seotud tugede ettevalmistamisega.
6. Ilmnes, et vormimisest tingitud jääkpinged põhjustavad pärast detaililt üleliigsete osade eemaldamist olulisel määral kujumuutust. Kujumuutuste vältimiseks tuleks detailid peale vormimist termilise töötlusega jääkpingetest vabastada.
7. Töötati välja soovitused detailide ning sammvormimise protsesside projekteerimiseks. Kasutuselevõtu iseloomustamiseks toodi terve rida näiteid reaalsete detailide valmistamisest.
8. Sammvormimise edukas kasutuselevõtt sõltub ennekõike oluliste piirangute kõrvaldamisest. Kõige olulisemad piirangud on madal täpsus ja tootlikkus ning seina õhenemine vormimisel.

Edaspidi vajavad uurimist alljärgnevalt nimetatud teemad.

- Hälvete kõrvaldamine elastse tagasivedrutuse kompenseerimise abil.
- Sammvormimise tarbeks spetsiaalsete tööradade loomise strateegiate väljatöötamine ja tarkvara süsteemides rakendamine, mis oleksid võimelised hälbeid kompenseerima.
- Kahe robotiga sammvormimise protsessi tarbeks tööradade loomise strateegia ja tarkvararakenduste väljatöötamine.
- Jääkpingete mõju uurimine peale üleliigsete osade eemaldamist.
- Sammvormimise integreerimine mitmeetapilistesse tootmisprotsessidesse.

Curriculum Vitae

1. Personal data

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Date and place of birth	26.05.1975, Rakke
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3. Education

Educational institution	Graduated	Specialty
Tallinn University of Technology	2002	MSc (Production Engineering)
Tallinn Technical University	2000	BSc (Production Engineering)
Technical College of Tallinn	1994	Car technician
Tallinn Secondary School No. 17	1990	Comprehensive education

4. Language skills

Language	Level
Estonian	Advanced
English	Intermediate

5. Special Courses

Period	Organization and topics
3.01-28.02.2007	University of Tartu, course "Supervising and feedback"
28.11-19.12.2006	Tallinn University of Technology, course "Pedagogy and teaching methodology"
26.06-27-06.2006	Semcon AB (Sweden), course "Optimization with OPTIMUS"
28.11-30.11.2005	Engineering Research AB (Sweden), course "Simulation of sheet metal forming using LS-DYNA"

6. Professional Employment

Period	Organization	Position
2001-2002	Tallinn University of Technology	Engineer
2002-...	Tallinn University of Technology	Researcher

7. Scientific Work

Publications:

Pohlak M., Eerme M., Küttner R., Product Development Problems of Statically and Dynamically Loaded Sandwich Structures, OST-2003 Symposium on Machine Design proceedings, Oulu, 2003, pp 29 - 37.

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8. Research interests

Incremental Sheet Forming, Reverse Engineering, Rapid Prototyping, Structural Optimization

Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Meelis Pohlak
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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2002	Tehnikateaduste magister
Tallinna Tehnikaülikool	2000	Tehnikateaduste bakalaureus
Tallinna Kõrgem Tehnikakool	1994	Autotehnika tehnik-mehaanik
Tallinna 17 keskkool	1990	Põhiharidus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti	Kõrgtase
Inglise	Kesktase

5. Täiendõpe

Õppimise aeg	Õppeasutuse või muu organisatsiooni nimetus
3.01-28.02.2007	Tartu Ülikool, koolitusprogramm "Juhendamine ja tagasiside"
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26.06-27-06.2006	Semcon AB (Rootsi), koolitus "Optimization with OPTIMUS"
28.11-30.11.2005	Engineering Research AB (Rootsi), koolitus "Simulation of sheet metal forming using LS-DYNA"

6. Teenistuskäik

Töötamise aeg	Ülikooli, teadusasutuse või muu organisatsiooni nimetus	Ametikoht
2001-2002	Tallinna Tehnikaülikool	Insener
2002-...	Tallinna Tehnikaülikool	Teadur

7. Teadustegevus

Publikatsioonid:

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8. Teadustöö põhisuunad

Lehtmaterjali sammvormimine, pöördtehnika, prototüüpide kiirvalmistus, konstruktsioonide optimeerimine