FOREWORD

This document has been prepared for AMT – The Association For Manufacturing Technology by the Engineering Research Center for Net Shape Manufacturing (ERC/NSM) at Ohio State University\(^1\). This Center was established on May 1, 1986 and works with companies interested in advanced manufacturing research. The focus of the ERC/NSM is net shape manufacturing with emphasis on cost-effective production of discrete parts. The research concentrates on manufacturing from engineering materials to finish or near-finish dimensions via processes that use dies and molds. In addition to conducting industrially relevant engineering research on a contractual basis for interested companies, the ERC/NSM has the objectives to a) establish close cooperation between industry and the university, b) train students, and c) transfer the research results to interested companies.

This report entitled “TECHNOLOGY ASSESSMENT FOR FORMING AND FABRICATING MACHINE TOOLS AND ACCESSORIES” identifies new developments, customer/user requirements, relevant and practice oriented R&D activities related to the metal forming machinery industry. A literature review was conducted using U.S., German, and Japanese resources. The scope of the study focused on the following points a) metal forming and fabricating machine tools, b) dies and tools for metal forming, c) software for process modeling, die design and manufacture, and d) new materials for advanced forming applications. The emphasis of the study was placed on R&D related topics.

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EXECUTIVE SUMMARY

The ERC/NSM has completed a technology assessment on forming and fabricating machine tools and accessories for AMT - The Association For Manufacturing Technology. The scope of the study focused on the following points:

- Metal forming and fabricating machine tools (Bending Machines, Forming Cells and Systems, Hot and Cold Forming Machines, Presses, Press Brakes and Shears and Special Purpose Forming Equipment).
- Dies and tools for metal forming.
- Software for process modeling, die design and manufacture.
- New materials for advanced forming applications.
- Worldwide survey with emphasis on U.S., Germany and Japan.

The emphasis was placed on R&D related activities. Thus, information that is easily available in company brochures, web sites and trade shows was not covered. In conducting this study we relied heavily on personal contacts with individuals in universities (especially in Germany).

The study was conducted as follows:

- Review of relevant technical literature from the U.S., Germany and Japan.
- Contact selected high technology oriented companies, world wide, that manufacture metal forming equipment.
- Contact selected European research laboratories and universities that work closely with industry.
The objectives of this work are:

- Identify new developments, customer/user requirements, relevant and practice oriented R&D activities related to the metal forming machinery industry.
- Assess the significance and relevance of the identified activities and trends for manufacturers of metal forming equipment and accessories.

Chapter 1 of this report gives recent developments in Sheet and Tube Forming Machines and Tooling. Sheet bending and shearing, blanking and forming cells, progressive die blanking and forming, stamping and transfer die forming, sheet hydroforming, and tube forming are all discussed. Research work for machines, tools, and process variations for the aforementioned categories is included.

Chapter 2 discusses recent developments in Billet and Rod Forming Machines and Tooling. Wire and rod drawing, forming and shearing, cold and warm forging and extrusion, and hot forging and extrusion are all discussed. Research work for machines, tools, and process variations for the aforementioned categories is included.

Chapter 3 provides recent research on advanced forming applications for new materials such as high strength steels, aluminum and magnesium.

Chapter 4 gives practical examples of the Finite Element Method used in industrial applications. Research results for FEM modeling of sheet forming, tube hydroforming, and forging are discussed.

Chapter 5 describes research efforts for Other Supporting Technologies in metal forming (e.g. tool coatings, process monitoring and control, and prototyping and rapid tooling).
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1. Sheet and Tube Forming Machines and Tooling

1.1 Sheet Bending and Shearing

1.1.1 Machines


- Laser has been utilized as an easy-controllable heat source of high power density in sheet metal bending.
- In the present paper, three-dimensional laser bending of sheet metals is studied using a pulsed YAG laser. The laser beam is guided through an optical fiber cable and irradiated on an 18Cr-8Ni stainless steel sheet, which is bent by thermal stress.
- Supporting pins hold the sheet while the laser is scanned by x-y table, which is numerically controlled via a personal computer. Experiments are performed by changing working conditions such as scanning speed, pitch and path of the laser. The three-dimensional shape of the formed sheet is measured. Figure 1.1.1.1-1 shows the experimental apparatus.

![Experimental apparatus for laser bending](image)

Figure 1.1.1.1-1: Experimental apparatus for laser bending
Figure 1.1.1.1-2: Scanning paths of laser and measured height distributions

- Grids, concentric circular and radial paths for scanning the laser are used, as shown in Figure 1.1.1.1-2, and the formed shapes are investigated. The sheet is formed into a conical shape in the case of scanning the laser in radial path and into a spherical shape by radial scanning with many stages.

- To improve the accuracy of the final shape, it is necessary that the three-dimensional shape of the deformed sheet is measured during irradiating laser beam and the obtained shape is used for controlling the working conditions.

- The need for development of a database for storing the working conditions for the typical deformed work shape and an intelligent system for determination of working conditions is stressed.


- Aluminum sections are being increasingly used in cars, in rail vehicles, airplanes etc. constructive requirements regarding cross sectional shape of the section and the curvature necessitate a high expenditure of tools in bending technology.

- The new section bending technology presented in this paper combines kinematic shaping with the advantages of elastic tools in order to achieve a maximum of bending (see Figure 1.1.1.2-1).

- Hereby the sections are bent using a rigid collar and a flexible polyurethane pad that is embedded in a solid steel retainer installed on linear tracks.
The relative motion between the roller and the retainer can be described as the path curve in an x-z coordinate system. Different path curves result in different possible contours.

The relationship between the path curve and the resulting curvature course is very complex because of the magnitude of factors influencing the forming process.

A computer assisted planning system is developed on self-learning neural networks. Neural networks are able to deal with high data intensity and multiple interrelated factors.

The neural network was trained for 12 different geometries. The deviations between the actual and required curvatures were analyzed and the path curve was locally corrected for the following processes.

Due to its high flexibility, the presented technique is especially suited for the generation of complex curvature courses in prototyping and in manufacturing of small to medium lot sizes.


In asymmetric rolling, the work piece is often bent to an unexpected shape. Its curvature may be caused by the speed difference or radius difference of the work rolls and depends on rolling variables such as ratio of the peripheral velocities of the top roll, bottom roll, etc.

Asymmetric rolling conditions cause an asymmetric tensile state in the rolling gap. Furthermore, asymmetric rolling is accompanied by some instabilities such as curving of the work piece after rolling, vibrating of the sheet, and the rolling stand.

A finite element simulation is performed using an explicit FEM program Abaqus that shows the influence of the initial plate
thickness and the influence of the reduction ratio on the bending of the workpiece in asymmetric rolling.

- The influence of various initial thickness and various levels of deformation are studied in this model.
- The bending of asymmetrically rolled sheet depends on its initial thickness, the degree of deformation and the average radius of the rolls.
- It is concluded from the simulations that with increasing initial thickness, the sheet would be bent downwards. With increasing degree of deformation, the material will be bent upwards.
- These parameters can be modified in such a way that the sheet is not curved after rolling. With this knowledge, a work piece could be rolled asymmetrically in more than one pass.
- A new rolling unit is manufactured which contains 3 rolls and the work piece is rolled in such a way that it doesn’t have any curvature after bending (see Figure 1.1.1.3-1).

![Figure 1.1.1.3-1: New Rolling System](image)

1.1.1.4 “Roll Forming of Parts with Variable Sections along the Length (Research)” Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines.

- Roll formed products are used in aerospace, automotive and construction industries. Often, these products have constant cross sections. It is expected that by increasing the geometric variations, the application of roll forming can be expanded.
- The method is based on conventional roll forming. Based on computer simulations, it is decided to design a flexible 12-stand roll forming machine.
- It is planned to introduce a stand that is driven not in length, but in lateral directions. By controlling the lateral motion of the roll axes in this stand, it will be possible to roll parts with variable section geometry.
1.1.2 Tools

1.1.2.1 “Development of Tooling and Process for Hemming of Aluminum Sheet (Ongoing Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

- Hemming of aluminum alloys is quite different from that of steel sheet and requires new die design and deformation sequence.
- A model die set has been developed that allows determination of optimum bending radii for hemming of concave and convex geometries.
- To evaluate the design a scaled-down (1:2) engine hood has been formed that has the same edge radii as the real part.


- Sharply bent corners are usually required for precision bending of sheet metal and building plate members. For sharp bending, the present study examined the method of first forming a V groove by pressing with a V-shaped punch onto a blank sheet before bending.
- The features of this method are that the strength is improved due to work hardening by punch indentation. A normal press is used for the indentation, so that no exclusive V-groove cutting machine is needed. Hence, the work time is reduced.
- Experiments are carried out to compare the bent part formed by groove indentation sheet, groove cut sheet and a sheet cut without groove. The part is compared for characteristics such as bend radius, mean value of equivalent stress, maximum bending load,
springback etc. Figure 1.1.2.2-1 shows a comparison between the experimental part and numerical simulations.

![Figure 1.1.2.2-1: Simulation and experimental result of the bent part after springback](image)

- The experimental results are verified with numerical simulations.
- The results obtained can be summarized as follows:
  1. The mean hardness and equivalent stress along the central line of indentation increases with increasing groove depth.
  2. The bend radius of the indentation groove sheet is about 10% greater than that of the groove cut sheet.
  3. The strength of the bent part is greater by about 1.2 times in groove indentation sheet than in groove cut sheet.
  4. The maximum bending load in case of groove indentation sheet is greater than the groove cut sheet except for a shallow indentation depth.


- This study involves the development of tooling that can be used in a brake bending press. The tooling consists of two rolls, one is rigid and the other one has an elastomer layer.
- The bending moment is generated by the penetration of the sheet into the elastomer roll, Figure 1.1.2.3-1. The process details are investigated using FEM and experiments.
- The advantages of this simple bending method are a) the roundness of the workpiece over its entire contour, b) good form and dimensional tolerances and c) the possibility of bending perforated, blanked or surface coated sheet blanks.

- Robots are performing an increasing number of operations in sheet metal forming nowadays. With the increasing complexity of the process and components, process automation is becoming more difficult. In the present study, a method is proposed which generates bending sequences of a sheet metal part handled by a robot.
- If a robot handles the parts, the best grasping positions for each bending and the number of repositions must be indicated in advance. Using the proposed method, feasible bending sequences with grasping positions are obtained and the sequences are sorted in the order of the number of repositions.
- In generating the sequences, several important features for the sheet metal bending are considered by dividing them into channels, which is one of the base features.
- The error accumulated during bending operation is calculated for each sequence, and set-up positions can be selected so as to satisfy the preferential tolerance.
- A computer simulation was done based on the proposed method. Illustrative examples and results of various simulation models are given.
- The proposed method assists the sheet metal process planner by allowing advanced planning of the best bending sequences and confirming if the robot can perform the handling operation.

- A new intelligent tool system for sheet metal forming is proposed, and a flexible L-bending control system, which uses several sensors incorporated in the tooling, is developed.
- This system is autonomous and capable of changing the shape of the tools and the pressure acting on the workpiece to optimize the forming process and improve the forming limit and accuracy.
- In this study, the springback characteristic in L-bending is assessed on-line using the intelligent tool system.
- Closed-loop control of flexible, high-precision bending is used to compensate for variations in the dimensions and material properties of the workpiece.
- The experimental results show that bend angles formed with very high accuracy have been obtained even with only limited knowledge of the material properties or thickness of the workpiece.
- This intelligent tool system significantly improves the bend accuracy and flexibility of the L-bending process. The work presented also indicates the potential of applying this system to making other forming processes flexible.


- Controlling springback in small radius press brake bending operations is motivated by the need to produce small lot parts of high quality.
- A new technique for springback control has been developed based on a simplified analytical model of material and tooling geometry variables.
- This technique requires the on-line measurement of loaded angle with a robust, high-resolution optical sensor that is insensitive to material surface finish.
- The design of the sensor minimizes systematic error due to placement on the press bed. Loaded angle measurement accuracy of less than one arc minute is achieved.
- In combination with a press ram position control scheme, this sensor provides a more accurate bending process necessary for the further development of precision, small-lot sheet metal assembly manufacture.
1.1.2.7 “Laser-assisted roll forming (Research)” Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

- Lightweight construction with steel is achieved by a plate thickness reduction and use of high strength steels. However, use of high strength steels results in a reduction of the processing ability, particularly the forming capacity.
- This project researches the possibility of laser-assisted bending and roll forming to compensate for the decrease in formability.
- Mechanical properties of the steel are changed during the forming process through partial heating up of the workpiece in the deformation zone via a laser beam. The laser beam causes a local reduction in yield stress and an improvement in formability.
- The effects are examined for laser-assisted bending and laser-assisted roll forming of dual-phase steels, complex-phase steels and martensite-phase steels.

1.1.3 Process Variations

- Continuous roller bending of plates is an effective process in the production of single seamed tubes of large and medium diameters.
- The process is capable of a wide range of various tube diameters from the smallest of just larger than the diameter of the top roller to the largest limited only by the handling capacity of the bender. It requires less investment in tooling compared to other bending processes.
- Relevant researches on roller-bending are reviewed and referred to. Current roller-bending machines are discussed.
- In particular, the versatility of the four-roll bender and its ability to generate better circularity, thereby helping to reduce material wastage and amount of subsequent machining, are examined.
- This paper discusses not only the design considerations, but also the working principles and some relevant bending mechanisms of the process.

For miniaturization of mechanical and electrical parts, accurate bending of thin plates has become important not only in the forming processes but also in adjusting shapes or positions of the parts after assembly.

To attain accurate bending of thin plate springs, spark forming in which a plate is bent by thermal stress due to electric spark is proposed.

Experiments are performed with plate springs of 50 to 70 micron thickness made of beryllium copper, pure titanium, pure copper, and 18Cr-8Ni stainless steel. The results are compared with those of laser forming. Figure 1.1.3.2-1 shows the experimental apparatus.

The effect of polarity of electrode, capacitance, charge voltage and sparking number on bending angle is studied.

Figure 1.1.3.2-1: Apparatus for laser and spark forming of thin plate springs

The working energy to required to obtain the same bending angle in spark forming is about 1/20 that of laser forming. Spark forming is effective for various materials while the effectiveness of laser forming is changed with working material.

The bending angle can be controlled with an accuracy of 1x10^-4 degree by the proposed method.

It is concluded that spark forming has advantages in the variety of applicable materials, efficiency of energy, cost and space required for the apparatus over laser forming.

1.2 Blanking and Forming Cells

1.2.1 Machines
1.2.2 Tools
This paper investigates the condition of constant line energy in which the ratio of laser power to scanning velocity is kept constant. Under this condition, the effects of velocity change on temperature, net energy input, strain rate and material flow stress are studied. Their collective effects on dimension, residual stress, hardness and microstructure are also presented. Numerical results are experimentally validated and used to study process transiency, and aid in understanding the complex and often conflicting effects of the condition.


This paper presents a review of the direct applications of high-power diode lasers for materials processing including soldering, surface modification (hardening, cladding, glazing and wetting modifications), welding, scribing, sheet metal bending etc. The specific advantages and disadvantages of diode laser materials processing are compared with CO₂, Nd:YAG and excimer lasers. An effort is made to identify the fundamental differences in their beam/material interaction characteristics and materials behavior. Also, an appraisal of the future prospects of high power diode lasers for materials processing is given.

1.2.3 Process Variations

1.3 Progressive Die Blanking and Forming

1.3.1 Machines


A nine-bar linkage, composed of a geared five-bar linkage and a slider crank four-bar linkage, is evaluated computationally. Motion analysis is performed on the proposed linkage mechanism. The nine-bar linkage can be applied to a mechanical forming press with extremely slow forming speed and very long dwelling time. The linkage shows good performance for force transmission. Power input by two gears provides a continuous and smooth force for the ram motion. Disadvantages of the nine-bar linkage are a) gears in the five-bar drive linkage may cause excessive noise b) link length design is difficult because there are many variables and some constraints.
must be compromised c) 25-35% variation in forming speed with constant ram velocity difficult to achieve.

1.3.1.2 “Innovative Press Concept for the Manufacture of Precision Microcomponents (Research)” Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

- Manufacturing of precision sheet metal components for the electronics industry requires new equipment and tooling for economic production. Conventional presses have too much force capacity and too little flexibility for this application. Furthermore, in progressive dies all forming systems are in one die set, which is difficult to set up and exchange.
- The objective is to design a new press drive that is flexible and applicable to a variety of sheet forming operations. The press drive should have variable load-stroke capability, provide small forces and high rigidity in vertical and horizontal directions and allow assembly of several drive units for a given application.
- The design solution is a direct drive unit that uses a linear motor drive (see Figure 1.3.1.2-1). The forming processes are divided into several modular operations, each conducted by a single drive unit. The drive units are small and compact and they can be assembled for a specific application. A prototype has been built for testing and evaluation.

![Figure 1.3.1.2-1: Linear motor drive press for precision forming](image)

1.3.1.3 “Investigation of the Dynamic Behavior of Linear Guides in Forming Presses (Research)” Prof. P. Groche / PtU –
Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

- Investigations in high-speed mechanical presses (up to 2000 RPM) show that the slide guides have a significant influence upon the horizontal precision of the presses. A slight horizontal shift between upper and lower tools may cause tolerance problems in the formed / blanked part and reduce tool life.
- The dynamic behavior and guiding tolerances of various linear guide systems are investigated experimentally as well as using FEM simulation.
- For selected guide designs, used in today's high-speed presses, experimental studies are conducted to determine the effects of velocities, temperature, lubricants and forces upon the dynamic behavior and horizontal tolerances of the presses and tooling.

![Figure 1.3.1.3-1: Investigation of the dynamic behavior of linear guides](image)


- Often it is desirable to modify and optimize the velocity versus stroke curve of mechanical presses. Thus, it is possible to reduce the velocity of the tool when it hits the formed part or to maintain pressure between the dies.
- The use of non-round gear drives offers an alternative to linkage designs (see Figure 1.3.1.4-1). This technology is being developed in cooperation with the University of Hannover and a medium size press company.
- Presses with non-round gear drives can now be built to load capacities of up to 600 ton. Major applications are stamping operations where it is desired that the press slide hit the blank at a moderate speed so not to damage the blank surface and lubrication.
Mechanical presses have high stroking rates and are very productive. The drive of these presses is displacement dependent, i.e. the design of the eccentric or crank mechanism determines the velocity versus stroke. It is desirable to modify the velocity versus stroke characteristics of a mechanical press in order to reduce the contact velocity when the blank holder hits the blank and to affect the deformation speed.

A drive system, which uses a planetary gearbox, has been developed and is shown in Figure 1.3.1.5-1. It is built as a simple unit for easy assembly during press construction. This system allows modification of the velocity versus stroke without reducing the stroking rate of the press (see Figure 1.3.1.5-2).

Presses equipped with this special drive are expected to improve the forming conditions in stamping and cold forging. Work is in progress to utilize the system in hot forging presses as well, where it is desirable to increase the deformation velocity and reduce the contact time.

- A 24 kN linear motor press was built from four 6 kN linear motors, and its functions were investigated. Figure 1.3.1.6-1 shows the underdrive structure of the linear motor press. The ram is supported by four guideposts with balls. Figure 1.3.1.6-2 shows the linear motor press.
The linear motor press allows bottom dead center accuracy to be improved markedly. The press uses a detector with linear scale to measure the position of the press ram accurately (see Figure 1.3.1.6-3). A learning control is used to eliminate the difference between the actual and set ram position. This learning control compensates for changes such as deformation of the press during forming, movement of the ram at "snap through" during blanking and thermal growth due to temperature fluctuations.
Figure 1.3.1.6-3: Linear scale for learning control

- Features of the linear motor press include the following:
  1. Press ram is moved with linear motors, which yields a simple drive mechanism.
  2. The motor output is used directly as the press output.
  3. Many linear motors must be used to realize a large press capacity.
  4. Maximum forming load can be produced at any stroke position.
  5. Stroke length, bottom dead center position and production speed can be changed randomly.
  6. Press ram movements can be programmed in any waveform as shown in Figure 1.3.1.6-4.

Figure 1.3.1.6-4: Various press ram movements

1 Normal crank motion
2 Slow approach and quick return
3 Vibratory motion at bottom of stroke

Figure 1.3.1.6-4: Various press ram movements
7. Use of a learning control allows the bottom dead center position to be maintained at an accuracy of ± 5 μm.
8. No mechanical wear is present except in the slide guides.
9. The press produces minimal noise from motors and stamping noise can be reduced.
   - Possible applications for the linear motor press are a) stampings where bottom dead center repeatability is important b) small lot production c) forming of thin sheets d) stamping of viscous materials such as resin and e) combined stamping including tapping, laser welding and injection molding.

1.3.2 Tools
   - Development of a hydraulic inertia damping system is investigated. Two systems are compared a) counter pressure force inertia damper and b) downward-blanking inertia damper.
   - Counter pressure force inertia damper uses a counter pressure force that provides inertial resistance to the punch.
   - Downward-blanking inertia damper uses damping cylinders, which are contained in the upper die plate and connected by rods to the blank holder, to provide inertial resistance.
   - Both devices reduce punch acceleration at breakthrough by applying an inertia resistance against the punch.
   - Unlike conventional hydraulic dampers, the present dampers in general eliminate the need for exact adjustment of the operation timing.
   - The developed dampers are very simple and can be contained inside or outside the press frame.
   - Both systems show noise reduction around 10 dB, irrespective of the work material, while only slightly increasing the blanking force.

   - Nitrogen spring technology is explained and the latest “controlled return stroke” and “variable force-stroke trajectory” springs are assessed.
   - Nitrogen, a nonflammable and nontoxic medium, is used in gas cylinders to provide blank holding force in dies. Nitrogen is also safe with regard to the use of lubricants.
Nitrogen springs offer the following advantages over conventional mechanical springs:

1. Provide full load on contact thereby eliminating the need for pre-load.
2. Exhibit a far less increase in spring force over spring travel as compared to conventional mechanical springs (see Figure 1.3.2.2-1).
3. One nitrogen spring can replace several conventional springs due to a higher force density than coil springs.

![Comparison of nitrogen and mechanical springs](image1)

**Figure 1.3.2.2-1: Comparison of nitrogen and mechanical springs**

Nitrogen spring systems can be classified into four types of overall systems, which are described below:

1. Self-contained gas springs (see Figure 1.3.2.2-2)
   - Can be ordered pre-charged or individually adjusted in the field.
   - Relatively high force increase over the stroke (30 to 70%).

2. Hosed system (see Figure 1.3.2.2-3)
   - Entire system is charged or discharged from a control panel.
- System pressure is uniform throughout and can be easily monitored and adjusted.
- Relatively high force increase over the stroke (30 to 70%).

![Hosed nitrogen gas spring system](image)

**Figure 1.3.2.2-3: Hosed nitrogen gas spring system**

3. Manifold system (see Figure 1.3.2.2-4)
- Pressure can be easily monitored and adjusted from a central control panel.
- Relative small pressure rise over the stroke (10 to 20%).

![Manifold nitrogen gas spring system](image)

**Figure 1.3.2.2-4: Manifold nitrogen gas spring system**

4. Tank system (see Figure 1.3.2.2-5)
- Pressure can be easily monitored and adjusted from a central control panel.
- Pressure rise over the stroke can be engineered to meet application requirements.

![Tank nitrogen gas spring system](image)

**Figure 1.3.2.2-5: Tank nitrogen gas spring system**

- Nitrogen spring designs can be classified into three categories:
  1. One-chamber systems (see Figure 1.3.2.2-6)
     - Piston and piston rod form a single unit with the seal placed on the piston and wiper on the piston rod.
- Upper chamber ventilated to atmosphere.
- Suited for short stroke with progressive force behavior applications.

Figure 1.3.2.2-6: One-chamber system

2. Two-chamber systems (see Figure 1.3.2.2-7)
- Nitrogen can flow from one chamber into another via a notched piston.
- More qualified for long strokes with small force increases.

Figure 1.3.2.2-7: Two-chamber system

3. Modified/sealed two-chamber systems (see Figure 1.3.2.2-8)
- A seal separates the upper and lower chambers.
- Gas connections are found at both chambers.
- Used in special applications such as delayed return systems, which are used to lock the blank holder in its lower position in order to avoid deformation of a drawn part, and variable force trajectories.
Several spring systems used for controlled return stroke are discussed.

Experiments conducted at the Institute for Metal Forming Technology (IFU), University of Stuttgart, show that variable force nitrogen spring systems can be used to increase part quality while making the process more robust.


The paper outlines an approach for the development of a new composite that is used for the design of progressive press tools. A series of preliminary experiments were conducted to evaluate the performance of the composite.

The aim of the study is to establish and define the optimal matrix-reinforcing material relation through experiments. Experimental investigations improved the strength and stiffness of the composite material.

The main characteristics of the composite are a) low specific weight b) high stiffness c) high strength d) fatigue and wear resistance.

Composite materials and elastomers can absorb the high velocity impacts, which are associated with some progressive die operations, better than their metal counterparts.

Tools requiring tight tolerances can be manufactured from composites.

Elastomers can be used as buffers, strippers, ejectors or springs.
Composite tools showed a better stress distribution compared to metal or alloy tools. Also, composites tools are more economical compared to steel and alloy tools.

1.3.2.4 “Controllable Nitrogen and Hydraulic Cylinder Systems for Deep Drawing (Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

- The use of nitrogen cylinders is common for controlling the blank holder force (BHF) in stamping. However, the conventional designs use cylinders that offer a constant pre-set resistance force against the downward motion of the slide.
- In this study, the objectives are to develop nitrogen cylinder systems that can be controlled to exert a resistance force that is variable as a function of slide stroke.
- As part of this study, the optimum BHF versus slide stroke variation is also estimated for given geometry and material of the deep drawn part.

Figure 1.3.2.4-1: Controllable nitrogen spring systems


- An overview about the basics of nitrogen spring technology and newly developed nitrogen spring technology is given.
- Nitrogen springs can be used in single action presses, which do not have a draw cushion, to generate blank holder forces. The springs are charged to a high pressure (up to 150 bar) and provide full load on contact. The increase of force (around 10%) over spring compression is much smaller than that of mechanical springs. Nitrogen springs also have a higher force density. Therefore, one nitrogen spring can replace several conventional
springs. Nitrogen is a safe medium because it is nonflammable, nontoxic and is safe with regard to the use of lubricants.

- Nitrogen springs are classified as one-chamber, two-chamber and modified two-chamber systems. An in depth discussion of these designs is given in 1.3.2.2. Figure 1.3.2.5-1 shows the difference between the three different spring designs.

![Figure 1.3.2.5-1: One-chamber system (a), two-chamber system (b), and modified two-chamber system (c)](image)

- A tank system presented by M. Schlegel is based on a modified two-chamber nitrogen spring system (see Figure 1.3.2.5-2). The system has an upper chamber, which is vented to atmosphere, and a lower chamber, which is connected to a tank. Adjusting a valve allows control over the spring return stroke.

- An autonomous spring system with controlled return stroke uses the upper chamber as an expansion volume (see Figure 1.3.2.5-2). This system has the advantage of less required space; but the disadvantage is a higher force increase over the stroke.

![Figure 1.3.2.5-2: Tank system (a) and autonomous spring (b)](image)

- Research has shown that a variable blank holder force over the draw depth can enhance forming in deep drawn parts. The Institute for Metal Forming Technology (IFU) of the University of Stuttgart, Germany, has developed a nitrogen spring system that allows control of the blank holder force over the stroke.
The system, shown in Figure 1.3.2.5-3, uses modified two-chamber nitrogen springs. A 2/2-way valve and adjustable throttle connect the upper and lower chambers of the spring. This makes it possible to control the spring force by changing the counter pressure in the upper chamber. Figure 1.3.2.5-4 shows the 18 controllable nitrogen springs incorporated into a side member die, along with a segmented elastic blank holder. The elastic blank holder allows for local variation in the blank holder pressure.

![Figure 1.3.2.5-3: Operation principle (a) and sample force behavior (b)](image)

Figure 1.3.2.5-4: Side member die with controllable nitrogen springs


Finite element simulations are common accepted die and process design tool in the automotive industry. However, the use of finite element simulation in designing progressive dies is not generally accepted, because most progressive dies include one or more deep-drawing steps followed by pinching, trimming and slitting etc., This paper presents a case study on application of finite element simulations in progressive die design.
The existing die design was initially simulated to predict the splitting and wrinkling occurred in the tryout stage. Figure 1.3.2.6-1 shows the possibility of splitting in the second operation as occurred in the die tryouts.

![Figure 1.3.2.6-1: Damage distribution in the sheet at the second stage of the process predicted by finite element simulation](image)

- The blank dimensions and die corner radius were varied in the FEA to find the optimum process condition that avoids wrinkling and splitting in the processes. The defect product obtained using finite element simulation for the optimized process parameters is shown in Figure 1.3.2.6-2.

![Figure 1.3.2.6-2: Thickness distribution at the last stage in the operation as predicted by FEM simulation for optimized process conditions](image)
• This example illustrates that process simulation using FEA can be used successfully to design new progressive dies and improve existing forming operations.

1.3.3 Process Variations

• Rotary blanking, which is a method of blanking and punching with rotating tools where the cutting tools are fixed to rollers (see Figure 1.3.3.1-1), is analyzed with discussions on advantages and limitations of the process.

Figure 1.3.3.1-1: Roller assembly for rotary blanking

• The rotary blanking tool depicted in Figure 1.3.3.1-2 is capable of punching sheet metals of up to 2.5 mm thickness at a speed of 80 meters/minute. Examples of products formed are cable throughs, armours or shelves.

Figure 1.3.3.1-2: Rotary blanking tool

• Advantages of the rotary blanking process are as follows:
  1. Output can be increased as the workpiece is fed continuously.
2. Investment costs are low.
3. Processing speed of the rotary blanking unit can be adapted to those of following processes making buffering areas between steps obsolete.
4. Drive of a rotary blanking facility is much smaller than that of a conventional press.
5. Blanking force and noise emission can be reduced due to oblique shearing (similar to a beveled punch in conventional blanking). Reduction in blanking force can be significant especially when blanking holes with a large length-to-width ratio.
6. Process is only viable for punched and pierced sheet metal products with a few number of rows and contours of large length-to-width ratios.

- Disadvantages of the rotary blanking process are as follows:
  1. Radial forces on the lateral parts of the punch and cutting edge can increase wear and decrease the quality of sheared edges. Also, the sheet is likely to be lifted when the punch leaves the workpiece, which can cause substantial machine vibrations.
  2. Cut line cannot be assumed as an image of the cutting edge of the punch (i.e. a circular cutting edge usually creates an oval shaped hole).
  3. Shearing gap constantly changes during the engagement of the punch. It is impossible to implement a defined and constant gap.
  4. Products with many rows of closely spaced holes in the feed direction are costly to manufacture using rotary blanking.
- It is advantageous to combine rotary blanking with other continuously processing methods such as roll forming.


- Water jets, accelerated by high pressure to three times the speed of sound, have become an essential tool in cutting technology. An overview of water jet cutting technology focusing on systems and application is given.
- Water jet cutting, schematically shown in Figure 1.3.3.2-1, can be performed with pure water or water with added abrasives. Cutting water jets have velocities up to 1050 m/s with 750-850 m/s typical.
Benefits of water jet cutting include a) reduced burring b) elimination of heat-affected zone c) reduced cutting times and d) ability to cut highly reflective materials such as aluminum and platinum.

A pressure intensifier, shown in Figure 1.3.3.2-2, is needed to produce the high fluid pressure. Hydraulic oil pressure acting on a piston results in a force on the plunger, which pressurizes the water in a small chamber. The ratio of effective piston area to plunger area is defined as the pressure intensification ratio.

Process variables for abrasive jet cutting include a) water pressure b) cutting speed c) abrasive size and type d) orifice diameter e) mixing tube length and inner diameter f) abrasive flow rate and g) standoff.

The following features of a workpiece must be considered a) material type b) material thickness and c) path geometry.

Examples of water jet cutting systems are shown in Figure 1.3.3.2-3 and Figure 1.3.3.2-4.
Due to lack of secondary processes, a water jet cutting system can be a very cost effective investment in processing tube, pipe and 3d molds. Cut speed and quality of cuts are two important factors. Sample parts manufactured by water jet cutting are shown in Figure 1.3.3.2-5.
Industrial demand for the fabrication of micro holes is growing. For example, micro holes that are several tens of μm in diameter are used in inkjet printhead nozzles.

A micro punch tooling is designed to produce holes of 100 μm diameter in 100 μm thick brass sheet. The tooling set up used for the experiments is shown in Figure 1.3.3.3-1.

A die clearance of 1 μm is needed if a clearance to sheet thickness of 5% is assumed. Since the clearance is very small, a precision linear motion guide system is required. The micro punching process must also be conducted under dust-free and temperature controlled conditions. Thermal growth must be controlled to prevent misalignment in the die set.

The micro punch tip must be designed to prevent failure from buckling and bending stress, which is due to misalignment. The die
is fabricated on a tungsten carbide sheet of 1.0 mm thickness using the micro EDM process. The tungsten carbide sheet is mounted on an AISI D2 die block.

- A major difficulty in the process is accurate alignment between the punch and die hole. An optical method is used to assure accurate punch to die alignment.
- Experiments show that holes of 100\(\mu\)m diameter were successfully punched in brass sheets of 100 \(\mu\)m thickness with a 5% clearance. Figure 1.3.3.3-2 shows the final hole geometry obtained.

![Figure 1.3.3.3-2: Punched micro-hole on brass (upper and lower sides)](image)

- Punch to die alignment must be improved for future work. The effect of various process conditions such as punch-die clearance, workpiece material and forming velocity must be investigated. Current efforts are geared at punching holes with diameter of 50\(\mu\)m.


- Straightening is essential to flatten the strip after uncoiling and to reduce residual stresses in the strip before stamping. During uncoiling, the curvature of the strip changes. Also, residual stresses may vary throughout the uncoiled material.
A system is developed to estimate the residual stresses and curvature of the strip after uncoiling. Further, this information is utilized for the adjustment of the upper rolls. The result is an adaptively controlled straightening machine that offers the possibility to produce very flat strip material with minimum amount of residual stresses.

Figure 1.3.3.4-1: Controllable straightening system

1.4 Stamping and Transfer Die Forming

1.4.1 Machines


New generation of press shops must offer tremendous flexibility in addition to high performance capacity to cope with the large variety of tasks.

Press manufacturers must develop innovative technology, which must not be limited to improving conventional technologies, but also include the development of new production processes.

Decentralized press shop planning is an evident trend with small but efficient facilities near the associated body-in-white to reduce transport distances and stock-keeping overhead.

Swinging shears may be combined with laser cutting equipment for the production of blanks.

Muller Weingarten has developed new approaches for hydraulic presses and forming lines with the following actions taken: a) development of a new drive system (see Figure 1.4.1.1-1) b) development of a flexible vacuum transfer system for hydraulic presses c) concept for new press lines d) concept for hydraulic vacuum transfer presses for large components.
Muller Weingarten has also developed a highly flexible vacuum transfer system for single presses and press lines that has the following advantages: a) each crossbar can be operated individually making it possible to implement any movement profile b) servo drives are used for the “Lifting/Lowering” and “Advance/Return” transfer functions.

Muller Weingarten is developing new implementation concepts for hydraulic press lines, which use the new crossbar technology. The requirements of the new press lines are a) press size designed for production of large and double parts b) bed width up to 5,000 mm c) tonnage of lead press up to 30,000 kN d) variable press spacing for optional installation with small or large press bays e) flexible crossbar system with electronic drive f) automatic tooling change including crossbar g) improved production capacity by new drive concepts and h) high-performance draw cushion incorporated in the lead presses.

1.4.1.2 “Hydraulic Deep Drawing Press with CNC Controlled 10-Point Cushion (Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

A 4000 kN press has been retrofitted with a CNC controlled multiple point hydraulic cushion system. Ten pins, which can be adjusted mechanically in height, are located on a draw cushion plate. The plate, in turn, has 4 CNC controlled hydraulic cylinders at four corners.

The system allows a) compensation of the elastic deflection of the blank holder, b) control of the variation of the blank holder force on various points of the blank holder and c) control of the material flow during deep drawing.
The press is used in research for determining the optimum blank holder force variation in deep drawing and stamping.

Figure 1.4.1.2-1: CNC controlled 10-point cushion system


The tryout of dies plays an important part in manufacturing of dies and in the production process in general. Tryout presses used in die shops do not reflect the characteristics of production presses, hence time consuming tests are conducted in the production shop. The same conditions apply after die repairs. Time consuming tryouts in production lines affects the productivity and the efficiency of the production equipment.

An innovative high speed hydraulic press that has the ability to emulate the forming behavior of different mechanical press types and brands with various drive systems and specific characteristics of slide motion in a production environment satisfies the desired needs of a tryout press.

Specific features of the high-speed hydraulic tryout press developed by Schuler are:
1. Accurate load adjustments
2. Inching mode for the slide
3. Reversal function at any point of stroke
4. Moving bolster with single point and multi-point cushions
5. Programmable slide speed profiles to simulate slide speed characteristics of mechanical and screw presses.
6. Advanced slide guide systems to simulate slide tilting in both mechanical and hydraulic presses due to eccentric loading.
A case study reports that hydraulic high-speed tryout presses reduce die tryout time by 12 days and save up to $360,000.


This paper describes recently developed metal forming processes, new methods in die manufacturing for metal forming applications and advances in metal forming presses.

Stereolithography techniques can be used to manufacture forming dies of plastics and other non-metals for aluminum sheets up to 1 mm. This method offers as a potential for low cost die manufacturing.

Manufacturing shearing dies by laminating thin plates with laser cut the shearing profile have been discussed and suggested as an alternative method for low cost production of shearing dies.

Hybrid presses combining both hydraulic and mechanical action (Figure 1.4.1.4-1) to compensate for low cycle time of hydraulic presses and high ram impact that expels lubricants in mechanical press operations.

Non-circular gears in drive system (Figure 1.4.1.4-2) can optimize the stroke vs. time characteristics of the mechanical presses to suite the process requirements.

Figure 1.4.1.4-1: Hybrid (hydraulic-mechanical) press

- This paper shows the benefits of single action presses with hydraulic multipoint cushion systems. For these press systems new die concepts have been developed.
- A die with a specifically designed elastic blank holder is presented. Blank holder forces can be achieved by controllable nitrogen cylinders, which are integrated in the die.
- Hydraulic cushion systems make it possible to build closed-loop control circuits for blank holder force control. This can achieve a robust deep drawing process.
- Figure 1.4.1.5-1 shows a hydraulic multi-point cushion system. Each cylinder has its own servo or proportional valve. By this it is possible to control the pressure between the binders and the blank in specific areas.

- Another possibility to build a multi-point cushion system is to have four hydraulic cylinders in the corner points acting on a cushion
plate with CNC height adjustable cushion pins as shown in Figure 1.4.1.5-2.

![Figure 1.4.1.5-2: Multi-point cushion system with 10 height adjustable pins](image)

- A segmented elastic blank holder is necessary in a multi-point cushion system to apply the cushion pin on specific area in the blank such that neighboring areas are not affected. Stiff segments connected by elastic joints build up such a segmented elastic blank holder. A segmented elastic blank holder can be achieved by pyramidal shaped ribs between the upper and lower plate of the blank holder as shown in Figure 1.4.1.5-3. To get an equal pressure distribution in one pressure area, the height of the blank holder should be equal to the distance between pins (Figure 1.4.1.5-3).

![Figure 1.4.1.5-3: Segmented elastic blank holder](image)

- The design of the upper binder has a great influence on the distribution of the blank holder pressure. Therefore, a strategy called prismatic die design has been developed to design the upper binders. A plane regular pattern, preferably honeycomb or square, is drawn vertical to the die bottom face (see Figure 1.4.1.5-4). The ribs between the cavities are relatively thin. On the contact side to the blank a thin plate closes the cavities. This design maintains uniform vertical stiffness of the upper binder to have positive effect of the variable blank holder force.
A way to realize a less expensive multi-point cushion system is to place a number of pressure-controlled hydraulic cylinders in the die. This makes it possible to adjust an individual optimal blank holder force for each cylinder over the stroke by a corresponding proportional or servo valve. By this we also get a multi-point blank holder system. Closed–loop controlled nitrogen cylinders can be used for this application.

With hydraulic cushion systems and the development of special measurement equipment which allows the measurement of forming parameters during the forming process, it is possible to build systems which are able to react automatically to changes of friction influencing production parameters like change of lubricant or amount of lubrication, so that the desired forming process can be maintained with a consistently good quality of parts without stopping production. The realization of such a system is based on a closed-loop control circuit (see Figure 1.4.1.5-6).

- This paper reviews the features and benefits of the Verson Dynamic Orientation System also known as DOS. This unique system, applicable to crossbar bar feeds, allows parts to move through seven separate axes at each operating station. This results in a transfer press that is smaller in size and can process with ease very complex body parts.

- Figure 1.4.1.6-1 shows the electronic transfer system attached to the transfer press. A resolver attached to the main gear monitors the rotation and sends a signal to the feed controller. The feed controller (Microprocessor) interprets the signal and sends commands to each of the drive controllers to start the feed. The encoders attached to the lift and clamping device monitor the motion and send signals to microprocessor. The microprocessor compares with the programmed position and the position of the slide to ensure the feed is in a correct, safe position, eliminating the possibility of interference between the slide and the feed.
Multi mode combines both tri-axis and cross bar modes of feeding system for a transfer press. One set of feed rails are configured for use with tri-axis and second set for use with cross bar with change over between modes accomplished during die change. Cross bar mode can be used for large unstable components while tri-axis modes are used for small and medium sized components (see Figure 1.4.1.6-2).

Dynamic Orientation System (DOS) was developed as a flexible and cost efficient solution for automotive stampers requiring large
cross bar presses. DOS has a dual cross bar system that can work independently in each station. A total of seven different motions can be performed while transferring a part between stations. This includes adjustment for off centering between the stations, rotation of $\pm 15^\circ$ right-left and tilting of $\pm 7^\circ$ up and down. The possible movement of DOS inside the press is shown in Figure 1.4.1.6-3. The DOS systems provide maximum flexibility and rigidity in handling complex parts.

![Degrees of motion of DOS](image)

**Figure 1.4.1.6-3: Degrees of motion of DOS**


- Despite higher demands for new products and trend towards low batch production, enchasing the productivity of the stamping plant is still a major target. This paper presents some of the technical innovations and state-of-art concepts for hydraulic production presses from Schuler SMG.
- The classical method of increasing the forming speed of the hydraulic press is to increase the motor capacities and the delivery rates of the pump in order to meet the higher demands.
- Schuler SMG has developed multiple cylinders for slide to increase the speed. Figure 1.4.1.7-1 shows the multiple cylinder system used in Schuler SMG presses. Three cylinders of the same capacity and volume are installed in the press. Depending on the load requirement, the press is operated with one, two or three cylinders. Maximum speed is obtained when a single cylinder is operated. Maximum force is obtained when all three cylinders are
used in the operation. The selection of the cylinders can be made manually provided the forming load required for a given part is known. Schuler SMG also devised a dynamic cylinder selection concept. A control panel monitors the load during the operation and gears extra cylinders as needed without altering the cycle time of the press.

![Diagram of pressure distribution](image)

**Figure 1.4.1.7-1: Multiple slide cylinders to increase the press speed**

- In addition to the existing slide cylinders, one extra compensating slide cylinder for each cushion cylinder is provided for the slide whose piston diameter corresponds to that of the cushion cylinder and which is located at the same axis as the cushion cylinder (see Figure 1.4.1.7-2). The individual compensating cylinders are connected to cushion cylinders by servo valves. The servo control is used to reduce pressure in the circuit by draining oil into the sump and to raise the pressure using oil from an accumulator.
- During a drawing operation the slide cylinders are activated by oil pressure from the accumulator. When the ram touches the blank holder and starts compressing, the circuit for compensating cylinders is cutoff from the accumulator and is connected to the corresponding cushion cylinder. The pressure in the hydraulic cushion cylinder and compensating hydraulic cylinder is maintained by oil from an accumulator.
- The benefits are as follows:
  1. The energy consumed for blank holding is almost zero.
  2. The heat generated during the cushion action is eliminated; hence the cooling capacity can be reduced.
  3. Slide tilting caused by a difference in the pressure generated by the cushion cylinders can be compensated.
Schuler SMG has developed an active parallelism control [Force-neutral parallelism control] system to counter balance the slide inclination that occurs in presses due to off center loading. Parallelism control is important to meet quality demands of the part and to increase die life.

Four single action cylinders mounted on brackets are provided laterally on the press slide. The cylinders, connected diagonally by hydraulic pipes, are supplied by their own hydraulic servo-control valves as shown in Figure 1.4.1.7-3.

Position encoders are installed on the slide to measure slide inclination during the stroke. This data is transferred to a separate control PC that determines the control signals for positioning the piston in the servo valves. The counter balancing force needed to compensate the inclination is created in the diagonal hydraulic circuit by changing the piston position in the servo valve. Due to the location of parallel control cylinders, this system operates force-neutrally, which means there is no additional slide force needed to overcome the parallelism control force. Depending on the job this system is capable of compensating off-center loads of up to 10000 kN/m with about 0.25mm/m maximum slide inclination and 200 mm/s forming speed.

The benefits of slide inclination compensation system are:
1. Parallelism control over entire stroke length.
2. Highly dynamic due to very short response time.
3. Force-neutral.
4. Suitable to simulate slide tilt in tryout presses.

Multi station press with implementation of the described innovations and with a fast drawing located at start will be the outlook for the hydraulic presses from Schuler. Advantages of the concepts are:
1. Uncoupled drawing station to produce complex parts with extreme draw depths.
2. Compact, space-saving design.
3. Easy die changes.
4. Low price.

Figure 1.4.1.7-3: Schematic view of Force-neutral parallelism control


- Transfer and tandem press lines are used for stamping high volume production components used in automobiles. Current market demand for niche and life style cars requires economical manufacturing process for small volume production. Transfer presses with existing dies are expensive and cannot be used for small volume production. To satisfy the demand for small batch production with reduced die cost, a new panel forming machine called Multi axial Panel Forming Press (MPF) has been developed. This paper describes the concepts, function and advantages of the multi axial panel forming machine.
- The MPF press completes all the metal forming operations in one stage using a compound die.
- Figure 1.4.1.8-1 shows the operation sequence of the MPF press.
- The MPF can be combined with high-speed laser cutter for final trimming that constitutes an economical manufacturing process for small lot production.
Features of the existing machine are a) tonnage of 700 tons and b) bed size of 3000mm x 2500mm.

The press is hydraulically operated with four cylinders for the main slide. The auxiliary slide, which is contained within the main slide, is typically used for trimming and is actuated by servo-controlled springs. The blank holder in the bed is hydraulically actuated and has an ejector.

Benefits of the MPF are:
1. Cycle time of the MPF is less than that of tandem line press.
2. Less capital investment, as only one die and press is required compared to tandem lines with 3-4 presses and dies.
Increasing complexity in part design and press shop processes as well as general demand for less lead-time in product development result in development of new aspects for tryout presses, and their integration in the process chain of tool making for sheet metal parts. This paper presents the requirements in a tryout press, new aspects in design of tryout presses based on modular constructions and a prototype built to meet the requirements using the new design aspects.

The tryout press should simulate as closely as possible the characteristics of a production press so that tryout time in the production facility can be minimized. The parameters that need to be mapped by a tryout press include:
1. Speed characteristics of the ram.
2. Tilting of the ram.
3. Force-path curve for cushions.
4. Pre-acceleration of the cushions.
5. Multipoint cushion system similar to production press.

A new method for designing the main drive, guidance of the ram, cushion system that was developed to meet the requirements of tryout press has been discussed.

A hydraulic prototype tryout press has been built based on the modular constructions. This tryout press can simulate the speed behavior of mechanical press, tilting behavior of 0.1 mm/m at a ram speed of 60 mm/s. The tryout press is equipped with a 16 pin multipoint cushion system and work in production mode and at die spotting mode where slow inching is required.
press systems on the system performance and demonstrates the inadequacy in the traditional tryout and simulation models. The elastic behavior of a mechanical double action press and its draw die is explained as they are commonly used in automotive stampings.

- Despite continuous development and wide acceptance of the FE in industry, try-outs continue to be a time consuming and unpredictable part of the stamping engineering process.

- In the FE simulations, once the blank holder is lowered and the blank is in contact with the binder surface either a constant force is applied or a constant gap is maintained between the blank holder and the die during the forming stage. However, during the process a drop in blank holder force of 30 % was observed towards the end of the stroke in a mechanical double action press. This drop in the force is due to the global compliance of the press system. This drop in the blank holder force is not modeled during the FE simulation. The drop in force could be controlled in designing the draw die such that the ratio of the blank holder system stiffness to the press stiffness is minimized.

- In FE simulations tools are represented as infinitely rigid surfaces or a solid of uniform stiffness. The standard justification being that the tool is much stiffer than the blank. This is not relevant in the region where the blank is clamped between the blank holder and the die. The distribution of contact pressure is controlled by the local compliance of the tool structure, thickness changes in the blank during forming, adjustments made to the surfaces during try-outs and the ram force. Forming simulation takes care of only the thickness change during the tryout.

- It is not possible to account for structural compliance characteristics of a particular tool in the FE model used for formability analysis since the forming simulation phase occurs during the binder design before the structure of the tool has been defined. Addressing it during the design of the castings for die could solve this problem. Consideration of stiffness during tool design would help in favorable pressure distribution during the process.

- Currently a significant amount of time in tryout is spent to bedding or spotting of binders this is done to maintain a uniform pressure distribution in the blank holder. During this process, an undeformed sheet is used. However, in the process, sheet thickness changes in the flange hence the pressure distribution may not be uniform. Therefore, a deformed blank should be used for spotting the dies during tryout.

- Balancer blocks are added to the tooling to maintain constant gap between the binder and the die as this reduces the mean pressure and changes the pressure distribution between the blank holder
and the die. The effect of balancer blocks on the pressure distribution is not considered during FE simulation and during spotting in tryout process.

- The metal bends and unbends in the draw bead where there is a normal force acting upwards that alters the pressure distribution in the binder. The effect of change in pressure distribution due to draw bead is not accounted for during spotting in the tryout process.
- Therefore adjustments made on tool surface through bedding/spotting based on the incomplete assessment of the forces acting on the binders result in poor correlation of the between the FE simulation results and the performance of the real tool. The problem requires new approaches to die design and tryout that reflects a better understanding of the elasticity within the press system. The elastic behavior of tools needs to be altered in design such that requires less spotting in tryouts and its representation in FE model is accurate and repeatable.


- In stamping, tryout presses must reflect the velocity-stroke profile of mechanical production presses. Thus, they must be able to emulate high as well as low slide velocities.
- In cooperation with a press builder and a hydraulic component manufacturer, the Fraunhofer Institute for Machine Tools and Forming Technology (IWU) in Chemnitz, developed a “hydro-link” press that has direct as well as accumulator drive. The 16MN press has a 16-point controllable hydraulic cushion. The slide velocity is 20-65 mm/sec with direct drive and up to 500 mm/sec with accumulator drive. The slide velocity can be programmed to emulate the velocity vs. stroke behavior of a mechanical press.


- Modern stamping technology for production of light body components requires new methods to form a) tailored welded blanks, b) high strength steels, c) aluminum sheet and d) magnesium sheet. Therefore special press and cushion designs are being developed for cost effective stamping of parts from these materials.
Some of the new developments in press design include: large bed sizes, larger forming loads and high stiffness of press frame and drive train. Increasingly, the following features are incorporated into modern press design: a) hydraulic overload protection, b) process monitoring, especially in forming of high strength steels (HSS), where the blank holder and punch forces are continuously measured. (thus, it is possible to determine when a split (fracture) occurs), c) setting of blank holder force by using multiple point hydraulic cushions that are individually programmable (Figure 1.4.1.12-1), and d) control of slide parallelism and active compensation of table deflection (Figure 1.4.1.12-2) to maintain closer tolerances on the large stamped body parts.

Figure 1.4.1.12-1: Multi-point blank holder cushion
Suppliers to automotive industry utilize their presses in a variety of flexible ways. For example, one stamping supplier uses its presses for large as well as small parts. In the latter case, considerable off center loading and tilting may occur, Figure 1.4.1.13-1.

In order to provide the accuracy and the flexibility desired by the customer, in cooperation with the customer, Schuler has developed a mechanical tilt compensation system. This system assures that the slide and the table of the hydraulic cushion remains parallel when off center loading is present.

The press has pressure pins at 4 corners of the cushion table and the slide. After some tilting occurs, the pressure pins provide the necessary reaction force to maintain the relative motion of the dies and the blank holder on the same axis.
Reducing cost and lead-time of tooling development is essential for low volume stamping production plants and prototyping. This paper describes an innovative-patented sheet metal forming technology developed in Japan that enables a sheet metal part to be formed directly from CAD data with the utmost precision.

The dieless forming technology involves a cold forming process that uses a three axis vertical CNC machine tool with a pencil like tool with spherical end mounted in the spindle head (see Figure 1.4.1.14-1).
The sheet metal to be formed is kept on the table that has roughly the shape to be formed. The tool, moving in concentric trajectories forms the sheet to the desired shape (see Figure 1.4.1.14-2). The movement of the tool is programmed like a cutting tool for machining.

The novel forming process is currently used in stamping plants in Japan and Europe for low volume productions.

1.4.2 Tools

1.4.2.1 “Vibrating Blank Holder in Deep Drawing (Ongoing Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

- During deep drawing the blank holder vibrates at a frequency in the range of 1-100 Hz.
• This design offers improved friction conditions and allows drawing deeper parts than with conventional techniques.
• Vibrating blank holder allows a more robust deep drawing process, i.e. the process can easily handle variations in material properties or lubrication conditions.

1.4.2.2 “Control of Blank Holder Force to Reduce Wrinkling in Deep Drawing (Ongoing Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

• In deep drawing (stamping) non-symmetric parts such as automotive sheet metal parts, it is possible to control material flow locally between the die surface and the blank holder.
• This is achieved by controlling the blank holder force during the forming stroke. As a result, product quality is maintained and improved even though process variables (material property, lubrication, sheet thickness) may vary during production.

![Figure 1.4.2.2-1: Blank holder force control](image)

1.4.2.3 “Optimum Design of Stamping Dies (Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

• The design of stamping dies has a significant influence upon the elastic deflection of the die as well as upon the distribution of surface pressure over the blank holder surface. Control of these pressures will allow improvements in stamping process and part quality.
Through extensive FE analysis and experimental measurements, a design concept has been developed for the application of multi-point cushions to control metal flow by controlling pressures over the blank holder surface.

The design has been evaluated through tests and found to be compatible for use with multi-point cushion systems.

Figure 1.4.2.3-1: Segmented elastic blank holder

1.4.2.4 “Forming of Tailored Blanks (Research)” Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

- Parts formed from tailored blanks help to reduce weight and increase crash resistance. Forming of this material, however, requires special die design considerations.
- Research is being conducted experimentally as well as using FEM simulations. The objective is to develop die design guidelines that consider the thickness differences of the welded blanks. Thus, segmented blank holders are designed to control metal flow and the position of the weld line.
- Two special dies are designed: one for a B-pillar and another for front left door inner. Thus, it is possible to develop and evaluate die design guidelines for stamping practice.

- During deep drawing of non-symmetric parts, the thickness of the blank varies at various locations around the binder. Thus, the blank holder must be elastically deformed to apply the necessary local pressure on the sheet in order to eliminate wrinkling while providing smooth metal flow.
- By using a relatively thin plate for the blank holder and a multi-point hydraulic cushion system, it is possible to control the local blank holder pressure and the metal flow at various locations of the drawn part.
- The system is a variation of the well known multiple point blank holder design and is shown in Figure 1.4.2.5-1. It is expected to improve the quality of the drawn parts and reduce the scrap rate.

- Exterior body panels for automobiles are more or less curved in two directions and critical consideration is given to properties such as dent resistance, surface quality, springback and dimensional accuracy. The effect of variable blank holder force on properties such as dent resistance, surface quality and springback is studied in this paper.
- In this study, experiments were conducted for double curved panels with three types of blank holders a) constant blank holder force, b) higher force at start and lower force at the end (strong-weak) and c) lower force at start and higher at the end of the process (weak-strong). The forces were kept constant in space and varied over the stroke.
- The dent resistance was greatest and springback was minimum for strong-weak force profile as the higher blank holder force at the start increased the strain on the face of the panel.
- The weak strong blank holder force profile provides maximum draw depth, as the walls close to punch radius are stronger because of less thinning hence recommended for deeply recessed parts.
- The blank holder force profile that needs to be used in the process depends on the geometry and desired final properties. Future work would use FEM analysis to predetermine the necessary properties of the panel and accordingly find a suitable blank holder force profile.

The use of conventional stiff blank holders in stamping operations results in local contact zones due to increased sheet thickness at the corners in the forming process. This local contact increases the blank holder pressure in contacting zones and reduces blank holder force in non-contact zones resulting in tearing and wrinkling in the drawn cup. An innovative blank holder concept presented in this paper applies a homogeneous blank holder pressure over the entire flange region and accounts for change in sheet thickness during the forming process.

In this study a pliable blank holder system was developed using an elastically deformable thin plate, which is supported on support elements that are attached to the table as shown in Figure 1.4.2.7-1. The dimension of the blank holder plate and the location of supports were decided by FEM analysis of the stamping process.

Experiments conducted with the pliable blank holder for a trapezoidal shape tool revealed that the blank holder plate deflected elastically to account for thickening in the restricted material flow zones. The pressure films used in the experiment read a homogeneous pressure distribution for pliable blank holder system compared to the rigid blank holders.

The amount of blank holder force required to successfully form part to same depth for the pliable blank holder system is high compared to the conventional blank holder. However, the operation window (forming limits) for the pliable blank holder system is large compared to the conventional system.

![Figure 1.4.2.7-1: Pliable blank holder system](image)

- This paper presents a review of current industrial research and development in blank holder technology, and its effect on the formability of sheet metals. The paper is divided into four sections with individual focus on a specific area.
- Section 1 describes fundamentals about formability in sheet metal forming and how formability depends on the strain history using Forming Limit Diagram (FLD).
- Section 2 describes the current research activities in developing experimental and analytical methods to determine the FLD and the significance of strain path in FLD.
- Section 3 demonstrates how blank holder force and the way it is applied influences the state of stress and strain in the part. A review on open looped and closed loop control of blank holder force is presented. It is also demonstrated how properly adjusting the blank holder force would increase the formability window.
- Section 4 describes how the real time control of blank holder force has been expanded in time and space. Significant developments in applying this technology in real world practice in Germany are reported.
- The optimum trajectory of blank holder force variation depends on the part geometry and the material type. Currently, research is done to estimate the optimum blank holder force for various part geometries.


- Reducing the cost and lead-time of tooling development is essential for low volume stamping production plants such as aerospace industry. This paper describes the detailed design, construction and evaluation of a rapidly reconfigurable tool for forming of sheet metal and composite aircraft body panels.
- The rapidly configurable tool consists of a matrix of 25 mm square spherically tipped pins contained within a rigid containment/clamping force. The pins are individually actuated by hydraulic force and can be positioned at different height to obtain different die shapes. The positions of the pins for a given die geometry are set using a closed loop control.
Experiments conducted with 4X4 matrix were successful and future work is focused on improvement in control system and pin design.


In stamping plants, despite the incoming materials having uniform quality, stamped parts show large variation in their quality. This indicates that there is a need for better understanding how the press/die and blank interact as a system in the stamping process. In this paper, the operating limits for a stamping panel have been established in production environment to have better control of the outcome of the stamped panel for different press settings.

In this Design Of Experiment (DOE) study, the punch speed, shut height and blank holder force are the variables studied for an automobile part and their effect on the stamping process was quantified by severity (thinning) and buckling (wrinkling).

DOE studies concluded that
1. Decreased punch speed resulted in increased severity and buckle index
2. Decreased shut height resulted in increased severity and buckle index
3. Increased blank holder force resulted in increased severity.


Surface deflections in stamped automobile panels are traditionally detected by time consuming techniques such as rubbing off the surface with whetstone or oil or a technician detecting using fingers or visual inspection. This paper presents a simple quantitative and convenient measurement method for surface deflections in automobile panels using an image sensing camera system.

In the image sensing camera system, a line is reflected on to the surface of the panel. The reflected line is viewed using a camera and the image is analyzed using mathematical techniques to find the surface deflections.

The rigorous mathematical techniques used in measurement and the procedure employed to calculate geometrical quantities are presented in the paper.
A case study is presented to show the measured deflections on the stamped panel, using image-sensing system and results were compared with conventional measurement techniques.

![Image sensing camera system](image.png)

**Figure 1.4.2.11-1: Image sensing camera system**


- Wide ranges of materials are used to produce low-cost tooling, ranging from specialized alloys to concrete, depending on the required production volumes. The change in die material has significant effect on the friction and hence the forming characteristics of the sheet metal. This paper discusses the friction for dies made of different materials commonly used in industry.
- The modified stretch draw test has been chosen to study the friction in sheet metal forming. Dies made of three different materials D2 steel, Kirkete and plastic were used in the test. Coated and uncoated sheet were used in the test.
- The effect of friction was studied using the blank holder force to form the part. Major strain and minor strain of the formed part along with percentage draw at the same cup height were measured.
- The plastic die exhibited the lowest friction followed by Kirkete and D2 dies.

• Prototyping and low volume manufacturing of stamping products requires flexibility in the forming tools that allows production of geometrically related products. This paper addresses a new concept of adaptable tooling that has been developed to produce geometrically similar products.

• Flexible metal forming tools are manufactured by a layered tooling structure. The active tooling elements are built with multiple layers of plates with thickness ranging from 1 to 20 mm and more. Layers are manufactured by conventional cutting technologies and/or laser beam cutting, wire electro-discharge machining or abrasive water jet cutting. The tool can be configured to different shapes by varying the plate in the layer thus production time for new tools can be shortened.

• The authors have presented an optimization program that selects the thickness of plate required and the number of plates for a given die geometry considering the tool loads, tolerance and roughness of the formed part, material properties of the plate and ease of assembly.

• Experiments were conducted with the adaptable tooling to prove its industrial application and to verify the optimization routine developed in this study.


• Multi-point forming has been characterized as a flexible forming system for sheet metal forming as multiple pins in the matrix can be rapidly reconfigured into different die shapes. This paper addresses the variations in multi-point forming and the defects commonly encountered.

• The four basic types of multi-point forming are a) multi-point die forming, b) multi-point half die forming, c) multi-point press forming and d) multi-point half press forming. The operation modes for the multipoint pins are shown in Figure 1.4.2.14-1.

• Commonly occurring defects are a) dimpling and b) buckling. The dimpling occurs due to the local deformation at the point of contact of sheet metal with pins. The buckling is due to lack of support during the forming operation.

• It is possible to eliminate springback in large panels through multipoint forming by repeatedly forming it more than the desired curvature thereby compensating for springback.
Figure 1.4.2.14-1: Four methods of multi-point forming

1.4.2.15 "Drawing of light weight materials with locally optimized properties (Research)" Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

- The aim of the project is to examine the possibilities of extending the forming limits of hardenable aluminum sheet metals. Application of process-adapted blanks is fundamentally investigated.
- Material properties of blanks are locally optimized for deep drawing by laser-induced heat treatment.
- Yield stress in the deformation zone is reduced to adjust an optimal material flow.
- Process steps needed for forming of complex sheet metal parts can be reduced.


- Higher demands of body-in-white designers concerning weight and strength of body components require a new choice in blank materials. High strength steel and aluminum alloys are increasingly used for structural parts. High strength steel and aluminum have low formability and high springback compared to the deep drawing quality steel. Therefore, they cannot be formed in a similar manner like deep drawing quality steel. Current research effort is focused
on developing controllable forming processes to manufacture a large spectrum of parts from aluminum alloys and high strength steels. This paper describes the application of active draw beads in drawing process to reduce spring back in the stamped components.

- The influence of spring back in the formed component by the drawing process parameters was investigated by modified Duncan Shabel test of drawing U profile.
- The change in the wall curvature of U profile was chosen as a criterion for evaluation of the spring back in the test. Tests were conducted with constant and variable restraining force for sheet material AA6111, ZStE340, St140 of two different thicknesses.
- The change in the wall curvature decreases linearly with increases in the wall stress and approaches zero.
- The change in the wall curvature decreases with increase in sheet thickness when the sheet is subjected to the same wall stresses.
- Aluminum alloys and high strength steel were more sensitive to spring back.
- The maximum value of restraining force was only important. The time during which highest restraining force acting in the test didn’t influence the spring back.
- A rectangular part was formed with active draw beads. During the drawing process, penetration of draw beads was adjusted to locally change the restraining process.
- Vertical movement of draw beads during the drawing process was achieved using a wedge mechanism that translates horizontal motion to vertical motion as shown in Figure 1.4.2.16-1. The tool was retrofitted with sensors to measure the wall stress during the process in the corners and in the flat walls where draw beads are provided.

![Active draw bead mechanism used in dies](image)

**Figure 1.4.2.16-1: Active draw bead mechanism used in dies**

- AA6111 sheet was drawn with three different trajectories of draw bead penetration during the process.
- Low draw bead penetration at the start and high penetration towards the end of the stroke during the drawing process resulted
in low wall stress and decreased spring back in the formed component compared to constant high or constant low penetration of draw bead during the entire process.

- Active draw beads provide the possibility of drawing the part with low stress levels at the start to pass through the critical fracture phase and provide high restraining force to eliminate spring back in the component. Thus, active draw beads increase the robustness of the process without compromising part quality.


- Multipoint cushion systems nowadays are used in drawing operation to locally control the metal flow between the flange and die thereby increasing the robustness of the drawing process. The cushion force can be varied locally by controlling each cylinder. Conventional blank holders are too stiff to influence the contact pressure locally. As a result, there is no direct relation between the cushion pin forces and the local contact pressure between the blank holder and die. This paper presents new concepts for designing flexible draw rings and stiff dies to enhance the possibility of local control of metal flow between the die and blank holder.

- Large dies and blank holders conventionally used in stamping automobile body parts are designed as box type or C-profile ribbed, cast, or welded constructions as shown in Figure 1.4.2.17-1. During the stamping operation, in the areas where the vertical ribs of the draw rings stand opposite to the blank holder the stiffness is very high while the stiffness is low at the center of the boxes. The variable stiffness leads to non-uniform pressure distribution between the blank holder and die as shown in Figure 1.4.2.17-2. Maximum pressure was observed at the ribs and zero pressure was observed at the center of the boxes.

Figure 1.4.2.17-1: Conventional blank holder with box type or C-profile castings
The author has presented a new concept called segmented-elastic blank holder to maintain uniform stiffness in the blank holder (see Figure 1.4.2.17-3). It consists of single segments for each cushion pin in the system, which are connected to each other by a thin bottom plate as shown in Figure 1.4.2.17-3. The pyramidal section ensures the blank holder force applied to each pyramid at the bottom is transmitted locally to the corresponding flange area at the top.

The locally varying distribution of blank holder pressure over the flange of the blank, and equal blank holder pressure on each segment of the segmented blank holder is feasible only if the stiffness of the die is uniform.

Uniform stiffness in the draw rings can be obtained by using prismatic sections. A prismatic draw ring is designed with many small hollow sections extruded vertical to the die base plane. The thickness of the webs is uniform and quite thin as shown in Figure 1.4.2.17-4. Figure 1.4.2.17-4 also shows that the extruded hollow sections can be rectangular, circular, triangular or honey comb patterns.
Finite element analysis of the conventional draw ring and blank holder with multipoint cushion indicated that an increase in the blank holder force by 100% in one of the cushion pins increases the blank holder pressure by 30%-70% in the corresponding location and 20%-30% in adjacent location. Using the segmented-elastic blank holder and prismatic draw ring, an increase in pin force by 100% increases the blank holder pressure at the corresponding area by 60%-90% and increases the blank holder pressure in adjacent areas by 10%-20%. Figure 1.4.2.17-5 shows the pressure distribution in the segmented elastic blank holder.

Using the concept of segmented-elastic blank holder and prismatic die ring, an experimental facility as shown in Figure 1.4.2.17-6 was built to draw rectangular parts. Aluminum blanks of 1 mm thickness were drawn to a cup height of 48 mm with a constant blank holder force. However, using variable blank holder force for each pin as shown in Figure 1.4.2.17-7, a rectangular pan of height 68 mm could be drawn in one stage.
Recent demands for small lot production of various shapes introduce requirements for new flexible forming technologies with less expensive dies. Several approaches have been used; for example, sheet metal forming using flexible dies with many cylinders arranged in a matrix, sheet metal bulging using spherical tooling and stretching using CNC machine tools. This paper describes a new flexible forming technique by incremental process using several standard elastic or rigid tools.

Figure 1.4.2.18-1 shows the principle of the flexible forming process proposed here. The process requires the use of elastic or rigid punch with a hemispherical or hemicylindrical head and elastic or rigid die with flat or hemicylindrical head.
During one elementary operation, the sheet metal placed between the punch and the die is pressed locally. This operation is repeated over the entire workpiece incrementally to form a specified surface.

The forming path of the punch and die can be circular or radial as shown in the Figure 1.4.2.18-2 and the forming path is CNC controlled.

The incremental forming process is controlled by mapping the strain of the formed part at each increment to the strain of the final part. The forming path is repeated until the difference in the strain is minimized. The strain in the final part for a given blank shape is calculated by geometric mapping.

A spherical shaped component was formed with the experimental setup to validate the control strategy described by the authors. This incremental process is advantageous compared to other flexible processes because hammering marks are eliminated due to incremental forming.

Figure 1.4.2.18-1: Principle of incremental forming

Figure 1.4.2.18-2: Forming path and definition of forming parameters

• Low formability of aluminum alloys compared to steel creates considerable problems in deep drawing of panels. This paper describes a method to improve the formability of aluminum alloys using active draw beads in draw tooling.

• Experiments and FE simulations were conducted for an asymmetric panel (see Figure 1.4.2.19-1) with three different draw bead trajectories.

![Asymmetric panel formed from aluminum alloy using active draw beads](image)

Figure 1.4.2.19-1: Asymmetric panel formed from aluminum alloy using active draw beads

• In the experiment and FE simulations, the draw bead penetration was increased initially to three different depths of 3 mm, 5 mm and 7 mm and decreased to 1 mm. The rate of increase and decrease is kept constant as shown in Figure 1.4.2.19-2. The parts were drawn up to 30 mm height.

![Trajectories for active draw bead in experiment and simulation](image)

Figure 1.4.2.19-2: Trajectories for active draw bead in experiment and simulation

• Strains were measured at three sections as shown in Figure 1.4.2.19-1 above. The FE simulation results and experiments were compared with FLD.

• Using the distance from FLD as the criteria, the authors concluded that an initial draw bead penetration of 5 mm could result in the deepest drawn cup for aluminum alloy A6114-T4. The formability of
aluminum alloys could be increased using active draw beads in the
die.

1.4.2.20 Muller, J., Heinze, R., (2000) “Use of Ceramic in Tools for
Sheet Metal Forming” New Developments in Sheet Metal
Forming, Institute for Metal Forming Technology of the
University of Stuttgart, Germany, pp. 467-492.

- Ceramic tool surface are characterized by a low affinity to sheet
  material such as steel and aluminum, high hardness and wear
  resistance. In sheet forming where large surfaces are formed at
  low speeds, the hydrodynamic lubrication range doesn’t exist and
  almost wear free forming is impossible. Although coatings are used
  in current tools to reduce wear, the demand on increased
  production results in more tool wear and loss of production time
  due to frequent breakdowns of coatings. This paper presents the
  properties of ceramics, guidelines for designing ceramic tools,
  friction and wear behavior of ceramic tools in sheet metal forming.

- Excellent resistance to high temperature and corrosion
  characterizes ceramic materials. The high hardness and wear
  resistance makes them well suitable for use in tribologically high
  stressed system such as sheet metal forming. However, ceramic
  materials due to their brittle behavior are not able to withstand local
  peak stresses. Ceramics commonly used are subdivided into
  silicate ceramics (porcelain, earthware, etc), oxide ceramics
  (Alumina, zirconia, etc) and non-oxide groups (carbides, nitrides
  etc). The last group is commonly used due its high hardness,
  Young’s modulus and strength. Manufacturing methods for each
  group are briefly described in the article.

- Designing with ceramic materials requires a fundamental rethink
  with regard to structures made from the ductile metallic materials.
  The following basic rules should be adhered to if possible when
  designing ceramic components a) avoid stress peaks b) minimize
tensile stress c) minimize reworking d) aim for simple forms and e)
take into account production specific factors. Construction
examples of ceramic tool materials are shown in Figure 1.4.2.20-1
below.
The authors investigate monolithic ceramics (silicon nitride and zirconia) and ceramic coatings (Mo, NiCrBSi/Mo WC/Co and TiMoCN/Co).

Tests were conducted on the ceramic tools and ceramic-coated tools using a strip drawing test setup. The tests were performed on deep drawn steel, galvanized steel, aluminum outer skin material and austenitic stainless steel. Unalloyed mineral oil was used as the lubricant.

The Coulomb’s friction coefficient in the experiment for ceramic tool silicon nitride with different lubricants for deep drawing steel was in the range of 0.08 – 0.06. For aluminum alloys, the friction coefficient values were in the range of 0.035-0.025. In dry conditions the friction coefficients for deep drawn steel and aluminum were high. With coated tools, the tribological system fails at high contact pressure. Thus, the high load bearing capacity of tribological system with ceramic surface (silicon nitride and zirconium) is noticeable.

To evaluate the friction conditions at the die radius in deep drawing a modified Duncan-Shabel test was used. When steel sheet was used, the experiments with silicon nitride gave lower friction force compared to grey cast iron tools coated with ceramic coatings. This behavior is apparent in small die radius. Aluminum sheets show similar behavior for various tool materials. In the non-lubricated state, there is no change in the friction force among the tool materials.

To evaluate wear behavior of ceramic tools, a deep drawing test was conducted on a drawing die with TiC/TiN coated tool and ceramic tool. The life of the coated tool in the experiment after every coating is shown in Figure 1.4.2.20-2. Ceramic tools used in the experiment had a maximum abrasion wear of 0.225 mm after processing 525,000 parts. Figure 1.4.2.20-3 gives the surface...
Ceramic tools display excellent lubrication and wear properties and therefore are potential materials for sheet metal tooling. Even though the ceramic tools are costly, significant maintenance related savings enables the productivity to be increased due to less press down time.


- Increased application of difficult to form materials such as high strength steels and aluminum requires the stamping process to be refined and much more robust. This can be achieved by controlling...
and reproducing the material flow from the binder to the punch. Conventionally, uniform pressure between the binder and the die is established by manually spotting the die and binder during the tryout stage. This is a time consuming process and highly dependent on the skills of the individual work. This paper presents the new development in binder technology to control and reproduce specific pressure distribution during the process.

- Segmented elastic binders consist of segments of pyramidal sections that are attached at the bottom by a thin plate to resist bending (see Figure 1.4.2.21-1). The pyramidal section is optimized such that the pressure at the binder-sheet-die interface is locally transmitted from the respective cushion pins and its influence on the adjacent zone is minimal.

![Figure 1.4.2.21-1: Conventional and segmented elastic binder](image)

- Experiments for the Hishida die with conventional binders and segmented elastic binders were conducted on a hydraulic press that has a four-point hydraulic die cushion system. The pin forces were adjusted by changing the length of the pins that transmit the force from the die cushion to the binder as shown in Figure 1.4.2.21-2.

![Figure 1.4.2.21-2: Binder system for four-pin hydraulic cushion press](image)

- Conventional binders with and without draw beads could produce a pan of less depth compared to the segmented-elastic binders for constant and spatial variation in the cushion pin force.
- A second set of experiments was conducted on a sample automotive fender. The die system for the fender is shown in Figure 1.4.2.21-3 below. A prismatic die with honeycomb section and segmented blank holder was used. Wrinkling and tearing was
eliminated with constant binder force for all pins. Part qualities such as waviness and non-uniform stretching were improved by varying the blank holder force among the pins.

Figure 1.4.21-3: Segmented-elastic die with uniform stiffness

- Using a pin force that varies in space among the pins and decreasing during stroke produced a better part.


- A system capable of varying blank holder force (BHF) with respect to both punch stroke and blank holder zone (location) is discussed. This technology is essential to deep drawing complex parts.
- In closed loop control of such a system, a computer generates a command based on the output of a sensor measuring punch force, punch stroke, etc. The computer sends the command to servo valves that control small short stroke cylinders. By controlling the pressure in these cylinders, the BHF can be varied with respect to both punch stroke and location.
- The advantages of such a system include:
  1. Because cylinders generate the BHF, it is independent of the press and less susceptible to thermal variations.
  2. Because a closed loop control system is used, frictional variations can be accounted for.
The system was tested with the deep drawing of spare tire housing. The BHF strategies for this testing included:
2. Flexible blank holder – BHF applied by short stroke cylinders. BHF constant with respect to punch stroke and location.
3. Profiled blank holder - BHF applied by short stroke cylinders. BHF constant with respect to location. BHF varied with respect to punch stroke.
4. Profiled and localized blank holder – BHF applied by short stroke cylinders. BHF varied with respect to punch stroke and location.

Other testing strategies included:
1. Deep drawing quality (DDQ) and higher strength (HSLA) steel.
2. Various BHF vs. punch stroke profiles.
3. Four BHF zones.

Test results can by summarized as follows:
1. All BHF strategies could draw DDQ steel to the normal depth.
2. The conventional blank holder could not draw HSLA steel to the normal depth.
3. The conventional blank holder could not draw DDQ steel to a depth 15 mm greater than the normal depth.
4. Only the profiled and localized blank holder could draw HSLA steel to a depth 15 mm greater than the normal depth.
5. Only the profiled and localized blank holder could draw DDQ steel to a depth 30 mm greater than the normal depth.
6. No BHF strategies could draw HSLA steel to a depth 30 mm greater than the normal depth.
7. A decreasing-increasing BHF vs. punch stroke profile was best.

It was shown that FEA could be used to optimize the BHF control strategy for a complex geometry.

- A pliable blank holder capable of deflecting such that a more homogeneous blank holder pressure is achieved is discussed.
- A rigid blank holder can cause increased contact pressures in areas of the flange such as the corner regions where the sheet thickness increases. Coupled with this increased pressure is a decreased pressure in the areas of the flange between the corner regions. Therefore, tearing is likely in the corner regions and wrinkling is likely in the areas between the corner regions.
- The surfaces of both the blank holder and the die can be modified to compensate for this, but the process is based on experience and is costly in terms of time.
- The pliable blank holder consists of a pressure plate supported by adjustable elements. The idea is that the pressure plate will deflect in the regions of the flange where sheet thickens such that the surface pressure will remain homogeneous across the flange. In addition, the lengths of the support elements can be adjusted for further optimization of the drawn part.

![Figure 1.4.2.23-1: Tool system with pliable blank holder](image)

- FEA results using PAM-STAMP showed that the pliable blank holder would in fact make the surface pressure more uniform.
- The pliable blank holder was evaluated using a trapezoidal tool to investigate the forming limits while varying the drawing ratio and the blank holder force for two different materials (DC04 and H340).
- The results of this evaluation showed that the safe working area for the pliable blank holder was much larger than that of the rigid blank holder. In addition, the results showed that higher blank holder forces could be used for the pliable blank holder than the rigid blank holder.
- The results indicated that the pliable blank holder could reduce the accuracy with which the blank holder force must be set and reduce the material dependency of the blank holder force.


- Rapid tooling for prototype or actual production is one of the essential requirements for reducing lead-time in large volume production. During the last several years, Ford Motor Corp., in cooperation with others, developed a practical metal deposition technique for rapid die and mold manufacturing. While the principle of the technology is not unique, the Ford Company appears to be first in putting this technology in practice.
- Ford's technique uses thermal spray technology to deposit metal spray on a ceramic part master that is back filled with epoxy to create a working die. The spraying is achieved by several robots that can cover a surface of 36in x 36in (914mm x 914mm). Work is in progress to develop a spray cell that can manufacture dies with a plan area of 96in x 96in (2438mm x 2438mm) which would make this die manufacturing method suitable for stamping dies where real cost and time savings are.
- It is claimed that this technology can produce dies within one to 12 weeks, depending upon die size. The process was licensed by several die manufacturers.


- The forming press described in this paper can vary the binder force both spatially and temporally in real time, allowing for complete customization of the Variable Force Binder (VFB) profile for a deep drawing application. Experimental results illustrate the VFB’s ability to regulate the material flow at localized regions around the blank perimeter. An electro hydraulic control system has been designed and implemented to track predetermined binder force trajectories in real time.
A modular actuator system with three, five and seven actuator systems were built (see Figure 1.4.2.25-1). It can be rapidly reconfigured to accommodate different parts shapes. Figure 1.4.2.25-2 shows three-actuator system configured for an axisymmetric part. Figure 1.4.2.25-3 shows a five-actuator system configured for a rectangular part.

Figure 1.4.2.25-1: Three point force actuator

Figure 1.4.2.25-2: Three point actuator configured for axisymmetric part

Figure 1.4.2.25-3: Five point actuator configured for rectangular part

Experiments conducted with these actuators indicate that the amount of material draw-in from the flange can be controlled locally along the perimeter by varying the actuator force at the respective locations.
A closed loop algorithm has been developed to control the force applied by each actuator based on the amount of material draw in at the respective location to compensate for earing in deep drawn parts.

Future work will be focused on using FEM and empirical methods to obtain the force trajectories for each actuator to form complex parts.


Use of coated steel and aluminum sheet in automotive body structures require a mechanical joining technique, such as clinching. Most of these are well known. However, improvements are necessary to satisfy new demands of the designers.

Research is being conducted on a) self-piercing riveting enhanced with local heating, b) self-piercing riveting with full rivet and c) self-piercing rivet with halbhohlniet.

Conventional clinching is being further improved by superposing a rotary riveting operation. These improvements are expected to improve the mechanical fastening techniques used in mechanical joining of sheet materials.


Dies and molds may represent a small investment in the overall production set up however they are crucial in determining lead times, quality and costs of discrete parts. The quality of dies and molds directly affect the quality of the produced parts.

Die and mold making covers various topics such as die and mold manufacturing, maintenance / modifications, technical assistance and prototype manufacturing for the customer. Process development and die try out are also important as they tie up the expensive production equipment and affect lead times.

Therefore die and mold makers are forced to develop and implement the latest technology in part and process design including process modeling, rapid prototyping, rapid tooling, optimized tool path generation for high speed cutting and hard machining, surface coating and repairs etc. This paper attempts to review the significant advances and practical applications in this field.
• High-end CAD systems with simulation techniques are used by the die makers to estimate the material flow and die stresses and optimizing the process parameters in the designing stage.
• High speed machining is well established while hard machining is being rapidly accepted. Optimized tool path generation to maintain constant chip load in machining complex sculpted surfaces is offered by some research centers as well as some software suppliers.
• Trend for unattended manufacturing is on the rise in the high wage countries. This mode requires robust processes, advanced tool path generation and best possible use of machines.
• Continuous training of the personnel is required by the die shops to cope up with the developments in process simulations and new cutter geometries for obtaining better surface finish and longer tool life.
• It is desired to machine the dies and molds in single setup. Thus deep cavities usually machined by EDM are first machined by milling using long and thin cutters.
• The cutting tools including geometry, substrate material and coating need continuous improvement in order to further improve the machining conditions.


• The quality of the deep drawn cup is largely determined by the rate at which a sheet is drawn into a die. In beginning of deep drawing, wrinkling could be problem and the BHF should be relatively large. As the flange continuous to draw in it becomes thicker and the wrinkles are less likely. At the same time, however, the fracture limit can be reached, and the part may fail unless the BHF is reduced and more material is allowed to draw into the die.
• Conventionally the BHF is applied using the helical, cup, rubber and polyurethane springs. These devices produce a linearly increasing BHF proportional to the press ram displacement, which is contrary to the desired constant or decreasing BHF patterns suggested by researches.
• This paper presents new control system for controlling the Blank holder force during the press ram stroke using Hydraulic/Nitrogen cylinders. The schematic view of the prototype circuit is shown in Figure 1.4.2.28-1.
Figure 1.4.2.28-1: Schematic view of hydraulic/nitrogen cylinder blank holder force control system

- In this prototype setup, the press ram that has the load cell forces against the blank holder force cylinder. The blank holder cylinder is connected to hydraulic circuit through proportional valve. The pressure required in the cylinder is maintained using nitrogen gas intensifier. The spool of the proportional valve and the load cell are connected to the data acquisition system.

- In the experiment, the press ram acts against the control cylinder piston that is maintained at desired pressure; as a result, the fluid in the control cylinder is forced through the proportional valve. The position of the spool in the valve maintains the pressure in the line. The spool position in the valve is adjusted electronically by the signal from the data acquisition system. Thus it is possible to control the pressure in the BHF cylinder as required by the user during the press stroke using the data acquisition system. The load cell attached to the ram measures the instantaneous load due to the pressure in the cylinder.

- Experiments were conducted by adjusting the spool position during the stroke. Descending step mode and ramp mode were simulated. Since blank holder was not used in the experiment the force measured by the load cell is called Control Cylinder Force (CCF). Figure 1.4.2.28-2 and Figure 1.4.2.28-3 show the control cylinder response as measured by load cell in press ram to the step mode signal and ramp mode signal to the spool position in the control valve.
Experiments prove that hydraulic/nitrogen BHF control system can be used in metal forming industry to simulate varying blank holder force control in time and space in the dies.

Some of the advantages of the hydraulic / nitrogen BHF control system are:
1. Closed system, no external power source required.
2. Can be used in both mechanical and hydraulic press.
3. Compact.
4. Low-cost system, uses commercially available components.
5. No in-die sensors.

High volume productions of deep drawn parts results in lot of wear problems depending on part geometry and hardness of the material. In particular, lead- radii in the blank holder and the die cavity are subjected to considerable rubbing that may lead to abrasive wear or galling. To overcome die break down due to excessive wear, various pressure – resistant lubricants in addition to heated treated and coated die surfaces are used.

An alternative method is to use inserts in the die made of sheet metal heat treated using gas or bath nitriding, or they can be chrome plated to further enhance their resistance to wear a shown in Figure 1.4.2.29-1.

Figure 1.4.2.29-1: Sheet insert in dies to reduce wear

Production trial were conducted with sheet die inserts using transfer press at BMW plant in Germany in collaboration with university of Munich concluded that:
1. Inserts without heat treatment can withstand for 1000 parts before producing galling and local welding.
2. Chrome plated inserts can withstand up to 1200 parts before producing galling and local welding.
3. Nitrided inserts can withstand up to 1900 parts before galling and local welding.

This investigation demonstrates that in selected cases of high volume production, the use of heat-treated sheet die inserts would be cost effective than using high alloy die steel inserts or coatings such as titanium nitride.

Discrete die concept is used in low volume production industry such as aerospace to produce sheet metal parts. In this concept, the tooling surface is made up of the hemispherical ends of individual pins, where each pin has a square cross section and can be independently moved up and down. This paper describes the scale up efforts from the laboratory setup to production setup and initial results obtained during testing of the reconfigurable tooling in an aerospace environment.

- The discrete die concepts have the following disadvantages:
  1. Right angle bends cannot be made.
  2. The radii of curvature formed are restricted by the size of the individual element of the pin.
  3. The load supported by each pin is restricted.

- Considering these restrictions, initially reconfigurable tool was developed for stretch forming application where the radii of curvatures are large and the individual pin forces are low.

- A full-scale tool was built with area of 4ft by 6ft with maximum vertical travel 1 ft for each pin. Each pin has cross sectional area of 1 sq inch and has hemispherical head. The assembly for each pin is shown in figure 1. Eight pins are grouped into a module each module can be attached and taken apart from the die without interfering with other pins. The entire die set had 336 such modules. The height of each pin is adjusted by servomotors that have encoders for closed loop control of its position. The height of each pin can be adjusted to an accuracy of 0.001 inches. The servomotors of each module are individually connected to shape controller that defines the height of the pins based on the CAD geometry to be formed.

- Initially aluminum sheet of alloy 6063 of thickness 0.063 inches were used to form saddle shaped components. All the components had local protrusions and dimples formed by each pin during the stretch warping process. To suppress the dimples a compliant polymer layer called interpolator the die and the sheet.

- Reconfigurable tooling allows incremental adjustment to the shape of the components to be formed. Using Deformation Transfer Function developed at MIT the deviation in the shape compared to CAD model is calculated and the pin position is adjusted to compensate for deviations.

- The successful demonstration of the design, construction and testing of full size reconfigurable tooling along with the development of methodology to control dimples and compensate for deviations in part geometries permits conceptualizations of a new sheet metal parts factory oriented towards rapid, small-lot production. The tools for such factory could be designed to cover a range of part sizes and complexities. In order to maximize the benefits of reconfigurable tooling, the part trimming should also be
done in reconfigurable tooling. Reconfigurable trimming devices are commercially available and consist of a bed of movable supports and a programmable trimming head.

Figure 1.4.2.30-1: Schematic view of the pin, module and full-scale model of the reconfigurable tooling

1.4.3 Process Variations

- Limiting draw ratio (LDR) in stamping operations is theoretically restricted to a maximum of 2.7 without friction, which decides maximum cup height that can be achieved in one stroke. This paper addresses design and application of ultrasonic vibration to the deep drawing process such that LDR values greater than 3.0 can be achieved.
- The authors have developed a compact vibration tool where the die and the blank holder can be vibrated radially and axially.
- LDR was increased from 2.58 to 2.86 for cold rolled steels, 2.38 to 2.77 for stainless steels and 2.68 to 3.01 for deep drawing steels by vibrating the blank holder only.
- Vibration of the die and blank holder in anti phase of 180 degrees increases the LDR compared to the vibration of the blank holder only.
• In the deep drawing process, stopping the vibration after the peak load is reached and increasing the blank holder force increases the LDR.
• Increase in the oscillation amplitude eliminates the wrinkles in the flange and decreases the punch load.
• Drawn parts by applying ultrasonic vibrations have lower hardness and less tensile residual stress compared to the part manufactured without vibrations.


• Sheet metal spinning is a complex forming process and knowledge on the interactions between process parameters and quality characteristics is not well developed. Thus, process development of metal spinning is time consuming and difficult. This paper presents a fuzzy logic control strategy for process design and monitoring of the spinning process.
• The fuzzy control unit for the spinning process allows closed loop control of the process during the operation and an offline working quality control closed loop which links the design of the workpiece, design of the process and the manufacturing process. The fuzzy control for spinning process is shown in Figure 1.4.3.2-1.

Figure 1.4.3.2-1: Closed loop fuzzy logic control system for optimizing spinning process

• The relationship between the process parameters and product quality were programmed through fuzzy logic in the control. The process design module generates an appropriate spinning process for a given component. During operation after each pass the workpiece quality characteristics are measured and the control system varies the parameters until significant improvement in the
quality is obtained in the next pass. This is repeated until the end of the entire process.

- The spinning force is measured from the spindle in real time and used as input in the fuzzy logic such that the parameters for each pass can be adjusted for change in the blank material properties.
- The spinning process is highly sensitive to wrinkles and the fuzzy logic is not able to prevent wrinkle formation during the process. The wrinkle in the process could be detected by measuring the axial force and tangential force at the support of the spinning lathe. However, the onset of wrinkling could not be detected.
- The authors plan to use explicit FEM codes to simulate the spinning process to study the characteristics of the process when wrinkles appear. The simulation results will be used to train the expert system for predicting the onset of wrinkling during the process.


- Work at The Ohio State University has shown that it is possible to stretch material to much higher strains than are expected based on conventional forming limit diagrams if high velocity metal forming is utilized.
- High velocity sheet metal forming can be implemented in a flexible manner by electromagnetic forming. Electromagnetic forming is accomplished by connecting a conductive actuator in series with a large capacitor bank with a high voltage charging circuit and fast-action switching. A transient magnetic field induces eddy currents in any nearby conductive materials. Resulting pressures from the electromagnetic field can become quite high and can easily exceed the yield stress of metal sheets.
- Researchers have shown that tensile instability can be delayed when the inertial forces are relatively large, which increases the formability of the material. Inertial forces tend to produce additional tensile stresses outside the neck, which increases total elongation.
- Electromagnetic forming can possibly be used to perform inertial ironing on sheet material. When a sheet moving at high velocity is stopped by a fixed die, large compressive stresses are generated in the through thickness of the sheet. These compressive stresses can produce lateral extensions in the sheet. Experiments at Ohio State have shown that very simple tooling can be used to produce coining-like effects.
• Wrinkling can be eliminated at sufficiently high velocity. Springback can also be reduced due to large through thickness compressive stresses that act at impact with a die.
• Developments in finite element codes are required to simulate the electromagnetic forming process with plasticity and inertia. With modest developments in simulation capabilities, electromagnetic forming will play an important role in the fabrication of advanced aluminum components.

1.5 Sheet Hydroforming

1.5.1 Machines


• A hydrodynamic deep drawing system is developed for use in a single-action press.
• The fluid filled die cavity is capable of reaching pressures up to 100 MPa.
• A blank holding system, capable of producing 1000 kN of force, is incorporated into the tooling. The author claims that the blank holding system is energy efficient and reliable.
• The hydraulic system consists of blank holding cylinders, die cavity and initial pressure system.
• A computer control system is capable of controlling the die pressure and blank holding force, which makes the system highly flexible.

![Hydrodynamic deep drawing system](image)

Figure 1.5.1.1-1: Hydrodynamic deep drawing system

A new conceptual design for a sheet hydroforming press is presented. Advantages of this proposed design are low investment costs for machines and tools.

The press concept is shown in Figure 1.5.1.2-1. Figure 1.5.1.2-1 shows that the press consists of two frame plates, which are connected by intermediate pieces and tie rods.

**Figure 1.5.1.2-1: Hydromechanical deep drawing press**

- The counter pressure pot is mounted on the press table, which is screwed to the lower cross clamps. Press table thickness is dependent on the nominal closing force resulting from the ram and blank holder forces.
- A high-pressure hydraulic unit, which contains quick disconnects for easy removal and installation of tooling, can be placed at the side of the table or in the press basement.
- A traveling cylinder controls machine ram movement during the non-working portion of stroke. Once the traveling cylinder closes the dies, spacers are positioned between the machine ram and press frame. The spacers act to transmit the forming load from the ram directly into the press frame while reducing closing time.
- Blank holder forces are applied by means of individual plunger cylinders located inside the tool. Blank holder cylinders can be controlled individually to produce an optimum distribution of blank holder pressure over the part.
- Three hydraulic cylinders produce the main ram movement and force. These cylinder forces are transmitted from the main ram into the machine ram and finally into the press frame. The operating sequence for the proposed design is shown in Figure 1.5.1.2-2.

![Hydromechanical deep drawing operating sequence](image)

**Figure 1.5.1.2-2: Hydromechanical deep drawing operating sequence**

- This concept for a new sheet hydroforming press has the following advantages:
  1. Independent regulation of the integrated blank holder cylinders.
  2. Direct application of blank holder forces integrated in the die.
  3. Optimum adaptation of the blank holder forces to various tool specifications.
  4. Shortest possible cycle times as the oil volumes of all hydraulic systems are reduced to a minimum.
  5. Low cost construction by reduction of the functional parts.

Several trends in the automotive industry appear to encourage the use of hydroforming sheet materials. For example, thin gage material from high strength steels is difficult to form with conventional stamping methods using hard dies. Small production volumes (5,000 to 30,000 units per year) require special production techniques that reduce the number of die sets required.

Schuler and other press manufacturers (Siempelkamp, Schnupp) have developed sheet hydroforming presses and tooling that allow commercial production of stampings. Research and development work considers the investment costs, the cycle times and the entire manufacturing concept to establish an economically viable process.

The technology has been used to manufacture prototype parts and is being expanded by using mechanical forming techniques (using inserts in the hydraulic container) together with hydroforming. Polymer tools are used since they are less expensive to manufacture. Flexible blank holders are developed to control metal flow during the deformation of the sheet.

Figure 1.5.1.3-1: Sheet hydroforming with stretching prior to deep drawing


A triple-action hydromechanical deep drawing press used by the Schnupp Corporation is shown in Figure 1.5.1.4-1. The press was developed specially for the active medium based forming method, and is deployed at Audi AG in Ingolstadt, Germany.
The hydromechanical deep drawing process is divided into the following states (see Figure 1.5.1.4-2):

a) plenum chamber is charged with active medium and blank is inserted
b) tool is closed by the position cylinder, which moves the blank holder onto the blank
c) blank holder is locked in place by lateral closing spacer blocks
d) hold-down cylinders (located above blank holder) and closing cylinders (located under press table) generate the desired blank holder force, which can be varied in time and space
e) punch contacts sheet and defines the stamp geometry
f) spacer blocks lock the punch in place at bottom dead center and calibration is done
g) spacer blocks retract and final part is removed.
• Travel of punch, blank holder pressure and active medium pressure can be varied in time independently of one another.
• Blank holder is a multi-point device capable of controlling local blank holder pressure, which increase process control.

1.5.1.5 Kleiner, M., Homberg, W., (2001) “New 100,000 kN Press for Sheet Metal Hydroforming” Hydroforming of Tubes, Extrusions and Sheet Metals, Institute for Metal Forming Technology of the University of Stuttgart, Germany, pp. 351-362.

• A 100,000 kN horizontal press for sheet hydroformed, developed by Siempelkamp Pressensysteme and Siempelkamp Guss, is installed at University of Dortmund, Germany.
• The press is to be used for research in high-pressure sheet metal forming (HBU). In high-pressure sheet metal forming, the rigid punch is replaced by a high-pressure fluid medium (see Figure 1.5.1.5-1). An advantage of HBU is that it allows optimal use of a material’s formability. Further process advantages can be realized by integrating punching or preforming operations in the HBU process.

Figure 1.5.1.5-1: High-pressure sheet metal forming process

• A major problem with HBU is control of flange draw-in, which could not be solved with traditional methods. Therefore, a software based flange draw-in control was developed. An essential component of this system is a multi-point flexible blank holder with flange draw-in sensors (see Figure 1.5.1.5-2). The system consists of 10 membrane short stroke cylinders located around the circumference, which control flange draw-in locally via a flexible blank holder.
The main objectives in designing the 100,000 kN hydroforming press were to realize a compact, inexpensive equipment that can produce the high locking forces required by hydroforming. Requirements for the press design are shown in Figure 1.5.1.5-3.

A horizontal press was chosen to achieve favorable handling of the working media. A compact design was achieved by using a prestressed cast press frame. The prestress is applied by winding the frame with 25 layers of high-strength armouring wire. The press layout is shown in Figure 1.5.1.5-4 below.
The working medium is supplied in a two-step process. A filling cylinder is used to provide high flow but low pressures (100 liters at a maximum pressure of 315 bar), while a pressure intensifier provides 5 liters at a maximum pressure of 2000 bar.


Manufacturers of Sheet Hydroforming presses are continuously developing new press concepts to a) reduce cycle time and capital investment, and b) increase flexibility and access to die area for improved handling.

A high pressure horizontal sheet hydroforming system (10,000 MN), with wire round cast frame, has been installed at the University of Dortmund, Figure 1.5.1.6-1.
1.5.2 Tools


- A novel tooling for hydraulic-pressure augmented deep drawing, which can be used in a single-action press, is developed and tested.
- The punch is actuated by hydraulic pressure at its small end. The press ram pressurizes the fluid in contact with the small end of the punch, thereby generating punch force.

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Figure 1.5.1.6-1: 10,000 MN horizontal sheet hydroforming press
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Figure 1.5.2.1-1: Hydraulic-pressure augmented deep drawing system
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- The hydraulic pressure pushes on the outer periphery of the blank during the drawing operation, which causes the cup to be drawn in a push-pull manner (flange is pushed by pressure and
wall is pulled by punch). This allows the cup to be drawn to a larger depth.

- Hydraulic pressure automatically generates a blank holder force that prevents leakage. The blank holder force begins at zero and increases to a maximum, after which it decreases to zero.
- Hydraulic pressure lubricates the top and bottom surfaces of the flange as well as the die radius, thus reducing friction.
- The process allows limiting draw ratios up to approximately 4 compared to 2.2 for simple deep drawing practice.
- Experimental work showed limiting draw ratios up to 3.5 for 1 mm thick aluminum blanks drawn on a single-action press.
- Future work includes investigations into the establishment of limiting draw ratios up to 4 in both theoretical and experimental work. Also, the drawing of square cups will be investigated.


- Advantages and disadvantages of hydromechanical deep drawing are discussed along with experimental results from an upper fuel tank tray.
- Advantages:
  1. Friction forces between the sheet and punch allow the possibility of greater draw depths.
  2. Stamped parts with complex geometries can be produced in a single operation without secondary wrinkles in the part walls.
  3. Die set is cheaper due to elimination of female die.
  4. Parts have excellent surface quality.
  5. Can generate convex/concave contours without a female die.
  6. Combined with hydraulic stretch forming, hydromechanical deep drawing can be used to increase the dent resistance in large automotive panels.
- Disadvantages:
  1. Presses with large ram forces are required due to the addition of high counter pressures.
  2. Expensive hydraulic systems are required to generate an “active” counter pressure.
  3. Slow production time means the process is only economical for low volume production (less than 50,000 parts/year).
  4. Formation of part contour radii is dependent on the maximum counter pressure.
- Process can be done “passively” where punch penetration into the fluid medium generates the counter pressure or “actively” where the counter pressure is generated by a hydraulic system.
An upper tray for a fuel tank is formed using hydromechanical deep drawing. An elastic segmented blank holder system is used to vary the blank holder pressure locally, thereby increasing the control of metal flow.

Results show that the upper fuel tank tray, which is difficult to form, can be produced using hydromechanical deep drawing with a segmented elastic blank holder. It should be noted that it was not necessary to spot-in the binders and draw beads were eliminated.

Figure 1.5.2.2-1: Hydromechanical deep drawing tool

Figure 1.5.2.2-2: Process limits of hydromechanical deep drawing


A process chain (see Figure 1.5.2.3-1) for the manufacturing of hollow bodies using unwelded sheet metal pairs in an integrated tool is discussed.
• The process steps are as follows:
  1. Docking – method of injecting fluid between sheets
  2. Preforming – deep drawing the unwelded blanks at relatively low internal pressures. Sliding between the upper and lower sheets is possible and most of the material distribution is done in this stage.
  3. Trimming – a cutting ring mechanically trims the sheets to prepare the welding surface.
  4. Laser welding – sheets are laser welded together by a robot located within the hydroforming tool.
  5. Hydrocalibrating – welded sheets are hydroformed at high pressure to produce the final geometry.

![Figure 1.5.2.3-1: Double sheet hydroforming process steps](image)

**Figure 1.5.2.3-1: Double sheet hydroforming process steps**

• Process involves uniform stretch drawing and deep drawing of the material, which imparts homogeneous strain hardening into the material.
• Factors influencing the material flow are a) blank geometry b) tribological behavior c) process parameters and d) part geometry.
• Initial blank geometry must be optimized to produce uniform movement of the material into the die and uniform contact pressure distribution in the flange area. Non-uniform contact pressure can cause premature fluid leakage.
• Material flow is controlled during forming with a blank holder pressure. The blank holder pressure is used to a) act as a seal to prevent leakage b) strain harden the sheets and c) control material draw-in locally.
• The critical geometrical features in the process are a) draw depth to draw width ratio b) concave inner contours c) concave flange geometries and d) small radii.
• Results show that preforming the blanks in an unwelded configuration first followed by hydrocalibrating of the welded blanks leads to the best product.


• Fluid pressure assisted deep drawing processes have been thoroughly discussed in this paper.
The hydromechanical deep drawing process is sub-divided into the following categories:

1. Deep drawing with fluid assisted blank holding (see Figure 1.5.2.4-1)
   - Traditional blank holder is replaced by fluid pressure
   - A thin rubber diaphragm transfers pressure to the blank flange.
   - Friction is reduced and LDR can reach 2.3, while productivity is slightly reduced.

![Figure 1.5.2.4-1: Deep drawing with fluid assisted blank holding](image)

2. Hydroforming process (see Figure 1.5.2.4-2)
   - Female die is replaced with fluid pressure, which is transferred to the blank via a thin rubber diaphragm.
   - Punch determines final part shape.
   - Fluid pressure must be controlled by a valve or pump.
   - Wrinkles form if fluid pressure is insufficient.

![Figure 1.5.2.4-2: Hydroforming with pressure and rubber diaphragm](image)

3. Typical hydromechanical deep drawing (see Figure 1.5.2.4-3)
   - Female die is replaced by fluid pressure.
   - Punch determines final part shape.
   - O-ring is used to prevent fluid leakage at the flange.
   - Blank holder functions as it does in conventional deep drawing.
4. Hydrodynamic deep drawing (see Figure 1.5.2.4-4)
   - Fluid can flow out beneath the blank decreasing friction at the flange.
   - Process can be used to form a cup with variable thickness or a hexagon cup.
   - Thin rubber diaphragm is not necessary.

5. Radial pressure deep drawing (see Figure 1.5.2.4-5)
   - Modification of hydrodynamic deep drawing process. LDR values can reach 3.3 to 3.6 in a single draw.
   - Fluid pressure pushes on the outer perimeter of the flange while the cup is drawn (push-pull operation).

   - SMG Engineering developed a hydromechanical drawing process that can be used to increase strain hardening and stiffness while improving quality in automotive outer panels (hoods, deck lids, roofs, doors and fenders).
   - Applications in Japan are a) reflectors of lighting equipment b) aircraft parts c) automotive parts and d) kitchen utensils.
Examples of parts produced in other countries are a) conical hollow bodies b) auto oil pan upper and c) tractor oil pans.

Hydroforming allows a 75% reduction in tool costs and 60% reduction in lead-time. However, it is only suitable for small scale or low volume production.

It is the author’s opinion that the hydro-mechanical deep drawing process has a lucrative future in the sheet metal forming industry.


Calculation of hydraulic pressure versus punch displacement is investigated for use in designing a short-stroke device for deep drawing of cups with punch and blank holding forces proportional to hydraulic pressure.

The device, which does not require sophisticated controls to regulate the punch and blank holding force, is shown in Figure 1.5.2.5-1.

![Short-stroke device used in experiments](image)

**Figure 1.5.2.5-1: Short-stroke device used in experiments**

- The author develops an equation to calculate the theoretical pressure versus punch displacement curve.
- Experiments are used to verify the theoretical calculations. Results show that the theoretical pressure equation is accurate at predicting the maximum process pressure.
The theoretical pressure calculation can be used in the design of tooling for deep drawing of cups with blank holding force proportional to punch force.


The paper discusses possibilities of sheet metal hydroforming with emphasis on hydraulic multipoint cushion systems for controlling blank holder force.

Multipoint cushion systems with segmented elastic blank holders, which are used to direct metal flow over the binder, provide control over wrinkling and tearing during forming by allowing local variation of blank holder force (see Figure 1.5.2.6-1).

Figure 1.5.2.6-1: Hydraulic multipoint cushion included in die

- Punch displacement can be used to generate the required forming pressure or a pump can be used to actively generate the pressure.
- If a pump is used to produce the fluid pressure, it is possible to have a prebulging of the blank. This prebulging will further work harden the part, which increases part stiffness and dent resistance.
- The Institute for Metal Forming Technology (IFU) of the University of Stuttgart (Germany) has developed a process that combines conventional deep drawing with hydroforming. The process uses either hydraulic counter pressure or internal hydraulic pressure to form the part in the hydroforming stage (see Figure 1.5.2.6-2).
IFU is also working with hydroforming of double sheet blanks, in which a fluid is pumped between blanks after they have been formed by conventional deep drawing. The fluid is then pressurized and the lower blank is formed into the die while the upper blank is formed into the punch (see Figure 1.5.2.6-3).

The author presents a review of recent developments in the hydroforming process.

Hydroforming uses oil, water or other fluid mediums as the punch or die and has the following advantages:

- Requires only one rigid tool half, which can be made from inexpensive materials. Therefore, tool costs and lead-time can be reduced by 75% and 60% respectively.
- Hydroformed parts a) have better quality b) are lighter, cheaper, stronger and stiffer c) use material more efficiently d) have better dimensional accuracy and e) have reduced springback.
- Parts can be very complex thereby eliminating the need for welded parts and reducing the total number of components in an automobile. Tailor-welded blanks can also be formed.
- Identical parts with different thickness can be made using the same tools.
- Process is very efficient and cost effective for production of small lot and prototype parts.
- Hydroforming has the following disadvantages:
  - Sharp radii cannot be formed.
  - Cycle times are slow; therefore, the process is limited to low volume production.
  - Dies must be highly polished.
  - Larger presses are required due to the high hydrostatic pressures that oppose the punch.
  - Hydroforming equipment is approximately 30% more expensive than conventional equipment.
  - Dies require more time to change.
- Characteristics of flat sheet hydroforming and viscous pressure forming (VPF) are discussed in detail.
  1. Flat sheet hydroforming
    - The process may fail by wrinkling if the fluid pressure is too low or tearing if it is too high.
    - Currently, fluid pressure paths are determined mostly by trial and error; however, it is expected that computer simulation will play an ever-increasing role in determination of the fluid pressure path.
    - Secondary wrinkle formation (sidewall wrinkling) can be controlled in sheet hydroforming since the blank is held against the punch under pressure.
    - Auto body panels, truck body parts, aerospace components, fuel tanks, washing machine drums and cooker cavities can currently be manufactured using sheet hydroforming.
  2. Viscous pressure forming
    - VPF process is similar to sheet hydroforming except the fluid is replaced with a strain-rate sensitive viscous pressure medium.
    - VPF can be used to form materials such as aluminum, high-strength steel and titanium in small quantities.
    - The pressure medium is occasionally placed on both sides of the sheet during the forming operation. Pressure differentials are developed between the upper and lower medium with pressure relief valves.
    - It is believed that the sheet is stretched more uniformly when the medium is placed on both sides of the sheet.

- Paper investigates the process of hydroforming unwelded sheet metal pairs. Models, numerical simulations and experiments have focused on various parameters that may affect the process window.
- The process of forming unwelded sheet metal pairs is shown in Figure 1.5.2.8-1.

![Figure 1.5.2.8-1: Hydroforming of unwelded sheet metal pairs](image)

- A docking system is needed to supply fluid between the two blanks. Examples of docking systems are depicted in Figure 1.5.2.8-2.

![Figure 1.5.2.8-2: Docking systems for hydroforming](image)

- Process control must allow draw-in of flange material into the forming cavity, as it has been shown to enhance formability since it has a direct impact on thinning. This is achieved by controlling the closing force, which directly influences the friction force under the blank holder.
A sealing limit provides the lower bound for the process. If the blank holder pressure is dropped below the sealing limit, leakage will occur. To high a blank holder force causes tearing in the sheet and represents the upper limit of the process.

FEM simulations have confirmed the importance of blank holder force control on optimum forming.

Unwelded sheets are used because they allow relative displacement between the two sheets. Therefore the sheets can be drawn to different depths.

Design rules obtained from numerical and experimental investigations are shown in Figure 1.5.2.8-3.

![Design guidelines for hydroformed parts](image)

**Figure 1.5.2.8-3: Design guidelines for hydroformed parts**


This paper discusses sheet hydroforming and dieless NC forming. Many examples of actual parts produced using these processes are given. Both processes can be used to form intricate parts while minimizing tooling costs and development time.

1. Sheet hydroforming
   - A sheet blank is formed by a rigid punch and hydraulic counter pressure, which acts as the female die. The process allows complex parts to be manufactured in a single step. Hydraulic counter pressure causes high friction forces between the blank and the punch which decrease localized thinning. Therefore, the limiting draw ratio (LDR) can be increased.
   - When the counter pressure increases past the set point of the relief valve, the fluid flows out between the blank and die. Thus, the die is lubricated and friction at the flange decreases, which allows material to flow into the die more easily.
Advantages of sheet hydroforming are as follows:

a) increased part accuracy
b) increased surface finish
c) uniform wall thickness
d) complicated shapes can be formed in fewer process steps
e) tooling cost is reduced
f) lower grade of blank material can be used
g) process is suitable for low volume production.

Figure 1.5.2.9-2 shows samples of complicated forming from the front section of a Mitsuoka Viewt vehicle. The number of parts required for the front section was reduced from ten to three by use of sheet hydroforming while the overall tooling cost was reduced and part quality increased.
Figure 1.5.2.9-2: Front section of a Mitsuoka Viewt vehicle

- Sheet hydroforming process can be used to produce parts from difficult to form materials such as aluminum and high strength steel. Figure 1.5.2.9-3 shows examples of automotive panels made from aluminum by sheet hydroforming.

Figure 1.5.2.9-3: Roof and fender hydroformed from 1.1 mm aluminum sheet

- Sheet hydroforming can be used to form parts with a high degree of accuracy. Examples of such parts, shown in Figure 1.5.2.9-4, are components that must provide uniform light distribution.

Figure 1.5.2.9-4: Hydroformed aluminum reflectors and parabolic antenna

- Complicated shapes that would normally be manufactured in several process steps can be manufactured in a single step using sheet hydroforming. Figure 1.5.2.9-5 shows sinks that normally require four operations by conventional methods but have been formed in a single step using hydroforming.
Figure 1.5.2.9-5: Stainless steel sinks hydroformed in one step (t = 0.7 mm)

- Figure 1.5.2.9-6 depicts the radial pressure deep drawing process. The figure also shows a comparison of a part formed by conventional deep drawing and a part formed by radial pressure deep drawing. As would be expected, the part formed by radial pressure deep drawing has a larger LDR compared to the part formed by conventional means, 3.3 to 2.0 respectively.

Figure 1.5.2.9-6: Radial pressure deep drawing

- The process can also be used to form pre-painted/pre-coated blanks, which reduces production steps. Figure 1.5.2.9-7 shows some examples of pre-painted and pre-coated parts manufactured by sheet hydroforming.

Figure 1.5.2.9-7: Pre-painted train panel (t = 1.2 mm) and range hood (t = 0.6 mm)
2. Dieless NC forming
   - Process can be used to form complicated shapes from various materials precisely and efficiently. The process does not require tooling, so development time is short. However, NC forming is only suitable for ultra small lot production (1~500 pieces per month) as the process is slow. Figure 1.5.2.9-8 shows the equipment used in dieless NC forming.

   Figure 1.5.2.9-8: NC dieless forming equipment setup

   - The main features of this system are a) tooling is not required b) can form complicated shapes c) easy operation with three axes NC programs d) requires little floor space and is quiet e) prototyping is faster and cheaper.
   - Samples of automotive components formed by dieless NC forming are given in Figure 1.5.2.9-9 while examples of general-purpose parts are displayed in Figure 1.5.2.9-10.

   Figure 1.5.2.9-9: Dieless NC formed automotive fenders (t = 0.8 mm)
1.5.2.10 Birkert, A., Nuebert, J., Gruszka, T., (1999) “Parallel Plate Hydroforming” Hydroforming of Tubes, Extrusions and Sheet Metals, Institute for Metal Forming Technology of the University of Stuttgart, Germany, pp. 283-296.

- New requirements from the automotive industry will cause parallel plate hydroforming to be used more extensively in the future. Parallel plate hydroforming can be used to produce components with complex geometries in one forming operation as shown in Figure 1.5.2.10-1.
Parallel plate hydroforming utilizes two flat or pre-shaped sheet metal pairs, which can be of differing thickness and are welded together at the edges. The welded sheets are inserted into a tool consisting of an upper and lower die. A fluid is introduced between the pair and the sheets are pressurized, causing the sheets to take the shape of the dies. The process is depicted in Figure 1.5.2.10-2.

Figure 1.5.2.10-2: Parallel plate hydroforming process schematic

A docking system is essential for introducing the pressurizing fluid between the sheets. Two typical docking systems are displayed in Figure 1.5.2.10-3. The sealing lance system has poor sealing at pressures above 800-1000 bar while the hemispherical sealing system can be used at pressures up to 1500-2000 bar. A disadvantage of the hemispherical system is that material close to the docking system is not allowed to flow.

Figure 1.5.2.10-3: Sealing lance (top) and hemispherical (bottom) docking systems

Parallel plate hydroforming allows for varying part circumferences as desired over the component length. Figure 1.5.2.10-4 illustrates the use of varying circumference in a component, which allows forming of complex parts in a single operation. Components with highly varying cross sections, such as A and B pillars, could be produced in one piece.
Material flow in the blank holder should be controlled locally by varying blank holder pressure.

Thickness of the sheet pairs does not need to be constant in parallel plate hydroforming. However, large jumps in sheet thickness are not realizable with the same material for the upper and lower sheets.

Parallel plate hydroforming imparts the following characteristics into the final parts a) high dimensional accuracy b) high bending and torsional rigidity c) high strength due to strain hardening d) weight reduction e) possibility of wall thickness variation and f) possibility of material variation within a component.

Differing draw depths in the upper and lower shells can result in forming difficulties, which are shown in Figure 1.5.2.10-5.

Flange alignment must be designed analogous to deep drawing. Problems can be expected for geometries highly rotated in terms of flange position relative to ram movement (see Figure 1.5.2.10-6). The optimum flange geometry has a normal flange line that is parallel to the ram movement.
Figure 1.5.2.10-6: Examples of feasible and non-feasible flange geometries
- Vertical component offsets can cause creases to form in the upper shell (see Figure 1.5.2.10-7).

Figure 1.5.2.10-7: Vertical component offset
- Non-uniform flange indentation can occur if the blank holder pressure cannot be varied locally (see Figure 1.5.2.10-8).

Figure 1.5.2.10-8: Symmetrical and asymmetrical flange draw in
- Sharp corner radii formed during the calibration stage can cause localized thinning due to reduced material flow from higher friction forces.

The paper discusses hydroforming of aluminum sheet metal pairs. A finite element analysis is conducted and compared to experimental investigations. A comparison is made between the hydroforming and conventional deep drawing process chains.

Production of low volume and complex hollow components will become very important for the automobile industry in the near future. Hydroforming of double sheets provides an interesting alternative to conventional processes.

Initially, a finite element analysis is performed to investigate the forming behavior of a hollow component. The results of this analysis are compared to experimental data. Results show that it is indeed possible to simulate the hydroforming of double blanks with sufficient accuracy. Numerical simulation can thus be used to improve the hydroforming process by providing an understanding of the material flow.

Experimental results show that a strength-optimized hollow component can be manufactured in a single forming operation. The formed part shows an even distribution of wall thickness and hardness in significant zones of the sheet metal. A forming limit analysis shows that the material's formability is not totally consumed and hence annealing is not required prior to further forming operations.

Hydroforming of double sheets holds considerable technological potential compared to conventional deep drawing. It is possible to achieve higher degrees of forming with hydroforming, while eliminating the need for intermediate annealing. Furthermore, aluminum sheets of different thickness can be employed to reduce weight while optimizing load carrying capacity.

Integration of hydroforming, joining and trimming into a single tool permits the forming of ready-to-install components in a single production step.

The hydroforming of double sheets allows a shortening of the process chain. Thus, material transport and smaller logistics efforts are required, thereby reducing the number of intermediate storage steps.

1.5.2.12 “Hydroforming of Sheet Metal (Research)” Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

Manufacturing of hollow components from sheet metal (for example, fuel tanks) is achieved by forming two separate parts via conventional stamping. The two parts are then welded together.

It is desirable to produce such hollow components in a single hydroforming operation.
Theoretical as well as experimental research is focused on a) determination of blank form, b) blank transport, c) seal technology and die design, d) shearing with hydraulic pressure, e) assembly of blanks using pressure, f) application of FEM simulation for die and process design and g) combination of various solutions to a practical manufacturing process.

Figure 1.5.2.12-1: Hydroforming of hollow component from sheet metal

In hydroforming of sheet, only one solid die is used and the pressure to form the material is applied by a hydraulic pumping system or by counter pressure achieved in a container (see Figure 1.5.2.13-1).

The process is being optimized to establish the practical conditions where sheet hydroforming is economical. Thus, overall process parameters such as pressure, punch velocity, punch force, seal design and die design are being determined. Furthermore, it is necessary to estimate the type of material (aluminum and high strength steels) and production volume (a few to several thousand) that make the process practical.

Guidelines for die design and optimum machine characteristics are being developed.
1.5.2.14 “High Pressure Hydroforming of Sheet Metal (Research)”
University of Dortmund and Siempelkamp Press Systems (Germany).

- The University of Dortmund has been conducting research on hydroforming of sheet for many years. Recently, it installed a novel 1000-ton horizontal hydroforming press (see Figure 1.5.2.14-1). The frame of this press is cast as a single piece but filament wound to support the needed press force.
- The press is being used to a) develop the parameters of hydroforming large sheet metal parts, b) determine the practicality of using a horizontal design that allows draining of pressurized water easily after each press stroke.
- The main objectives of this research are to form thin gage high strength steels as well as aluminum alloys. University of Dortmund’s experience in conventional sheet hydroforming is being used extensively to introduce the use of horizontal high-pressure hydroforming for economic production of large automotive panels.
New manufacturing technologies such as hydroforming can prove to be more flexible and efficient while allowing more complex shapes to be formed with better quality.

Hydroforming is accomplished using one of two techniques a) pressurizing a fluid with tool movement and b) using an external pump to pressurize the working medium.

Advantages are a) higher drawing ratios b) better shape and dimensional accuracy and c) better residual stress distributions (less springback).

Hydromechanical deep drawing has recently been used in the Japanese automobile industry to successfully form large surface parts. Pre-bulging large panels prior to hydromechanical deep drawing can increase the dent resistance of the panel.

“High pressure sheet metal forming” (HBU) is characterized by the use of an intermediate plate that serves as a blank holder and sealing apparatus (see Figure 1.5.2.15-1). Variation of blank holder force, working media, pressure and volume flow results in a change in strain path. The strain path can be optimized to produce the highest quality part possible (optimal use of formability). The HBU process can also significantly reduce the number of process steps required to form the part.
Figure 1.5.2.15-1: High-pressure sheet metal forming process (HBU)

- Accurate and reproducible control of flange draw-in can be difficult to achieve due to complex tribological conditions. Investigations have shown that a multi-point blank holder system can be used to effectively control flange draw-in in a reproducible manner. Flange draw-in can be further enhanced by oscillation of the blank holder force.
- A multi-point blank holder system based on membrane-shortstroke-cylinders has been developed at the University of Dortmund (Germany). The system is shown in Figure 1.5.2.15-2. The main features of the system are a) fast actuators, distributed across the circumference, for local application of blank holder forces b) flexible blank holder for transmission of forces to the sheet c) sensor system for detection of process variables and d) software based control of flange draw-in.

Figure 1.5.2.15-2: University of Dortmund multi-point blank holder system
Integration of auxiliary operations into hydroforming, such as punching, will shorten the process sequence and make the process more economical. An attractive approach to in-process punching is utilizing fluid pressure with a sharp cutting edge. This technique is also being evaluated experimentally and numerically at the University of Dortmund (Germany).

“Pneumomechanical deep drawing” (PMT) is a combination of hydroforming and conventional deep drawing. The process, which is shown in Figure 1.5.2.15-3, uses a gaseous medium such as compressed air to pre-form the blank. A rigid punch and die impart the final shape to the component. Advantages of PMT are a) production of a more convenient pre-form geometry b) increased strain hardening (increased dent resistance) and c) allows for minimization of sheet thickness.

![Figure 1.5.2.15-3: Pneumomechanical deep drawing process](image)

1.5.2.16 Krei, M., (1999) “State of the Art of Sealing Techniques for Hydroforming” Hydroforming of Tubes, Extrusions and Sheet Metals, Institute for Metal Forming Technology of the University of Stuttgart, Germany, pp. 441-462.

State of the art sealing techniques for hydroforming of parallel sheets are discussed with functional descriptions.

Docking system developed by Krupp-Hoesch AG and used by Krupp-Drauz GmbH (see Figure 1.5.2.16-1).

- Sheet metals need to be welded together. The lower sheet must have a hole with a collar.
• Sheet metals pressed onto the hemispherical projecting part of the lower die during die closing. Upper sheet expands into a spherical depression in the upper die until the die is fully closed.
• Metallic seal exists between the lower sheet and the spherical projection. Fluid medium is introduced through the spherical projection on the lower die.
• Docking system must be placed in an area where metal flow is minimal since metal flow is restricted by the spherical projection on the lower die.

Figure 1.5.2.16-1: Docking system using spherical projection on lower die

• Docking system splitting chisel developed by Schuler Hydroforming GmbH (see Figure 1.5.2.16-2).
Two pieces of sheet metal are welded together except in one area. A splitting chisel penetrates the unwelded portion when the die is closed.

Sealing is caused by plastic deformation of the sheet metals around the splitting chisel.

**Figure 1.5.2.16-2: Splitting chisel docking system**

Docking system with inserted connecting branch developed by Laserzentrum Gemeinnützige Forschungsgesellschaft mbH (see Figure 1.5.2.16-3).

Connecting branch is inserted in an unwelded flange area of the sheet metals. Plastic deformation in the sheet around the connecting branch causes sealing when the dies are closed.

Several docking systems can be integrated in parallel to allow faster filling.

**Figure 1.5.2.16-3: Inserted connecting branch docking system**
- Docking system ring channel developed by Laserzentrum Gemeinnützige Forschungsgesellschaft mbH (see Figure 1.5.2.16-4).
  - Medium filling is performed through a ring channel formed by the clamping surface of the die halves. A special combination of material and surface qualities enable the medium to penetrate into the parting plane of the two sheets.
  - An elastomer seal between the sheets and die prevents leakage of the working fluid.
  - Sheets are initially unwelded and can be welded together after forming.

![Diagram of docking system ring channel](image.png)

*Source: Patent DE 195 35 870 C1*

**Figure 1.5.2.16-4: Ring channel docking system**

- Attached connecting branch developed by Bayerisches Laserzentrum Gemeinnützige Forschungsgesellschaft mbH (see Figure 1.5.2.16-5).
  - Connecting branch is directly attached to an area of the sheet metals.
  - Two techniques for sealing are available a) connecting branch welded to sheet and b) seal created by pressing the connecting branch against the sheet with elastic force.
  - The connecting branch must displace vertically with the workpiece materials.
Figure 1.5.2.16-5: Attached connecting branch docking system

- Docking system using a distance plate developed by M. Kleiner (see Figure 1.5.2.16-6).
- A distance plate is inserted between two unwelded sheets.
- Distance plate supports the sheets, provides a means of introducing the working fluid and contains elastomer seals that prevent leakage between the sheets and plate.

Figure 1.5.2.16-6: Distance plate docking system

- Sealing system in sheet parting plane (see Figure 1.5.2.16-7).
A hollow-drilled axial plunger is placed between two welded sheets. The working medium is introduced through the plunger. Sealing is provided by metallic contact between the welded sheets and axial plunger.

**Figure 1.5.2.16-7: Docking system using hollow-drilled axial plunger**

- Filling and sealing in the flange area (see Figure 1.5.2.16-8).
- Two sheets are welded prior to processing. One sheet is provided with a hole in the flange area.
- A spring assembly pushes a pressure plate against the sheets. Working fluid is introduced through the pressure plate and sheet containing the hole. O-ring seals are used in the pressure plate to prevent leakage.

**Figure 1.5.2.16-8: Docking system using pressure plate in flange area**


- Combination of conventional deep drawing followed by hydroforming is studied with experimental and numerical results (material is low carbon steel). The principle of this process is shown in Figure 1.5.2.17-1 below. Initially the blank is deep drawn using a rigid punch and segmented elastic blank holder (provides local control of material flow). Then a cavity is hydroformed in the center of the deep drawn part.
Figure 1.5.2.17-1: Deep drawing and hydroforming process combination

- Experimental and numerical (FEM) investigations studied the so-called "Hishida" geometry (see Figure 1.5.2.17-2).

Figure 1.5.2.17-2: “Hishida” geometry used in investigations

- FEM simulations are done in two stages a) conventional deep drawing to a depth of 70 mm and b) hydroforming a cavity to a depth of 15 mm. It is important to note that the stress-strain history from the deep drawing process is carried over to the hydroforming process.
- Figure 1.5.2.17-3 shows the thickness distribution on the bottom of the pan at the end of the deep drawing process (initial sheet thickness is 1 mm). The figure shows that the deep drawing process should not significantly affect the hydroforming process since the material thickness does not change appreciably in the center of the part.

Figure 1.5.2.17-3: Thickness distribution after deep drawing to 70 mm

- Figure 1.5.2.17-4 shows the plastic strain distribution after hydroforming a cavity in the part. It can be seen from the figure
that the largest strains will occur where small radii are formed. It can be concluded that cracking may occur in the R10 corner.

Figure 1.5.2.17-4: Strain distribution after hydroforming cavity

- The tooling used for experimental investigations is shown in Figure 1.5.2.17-5 below. The tooling utilizes a segmented elastic blank holder to control material flow locally during the deep drawing stage.

Figure 1.5.2.17-5: Experimental tooling

- Experimental procedure is as follows: a) lubricate blank with non-alloyed mineral oil (5 g/m² on each side) b) place blank in press and complete deep drawing to 70 mm c) engage seals in the counter pressure pot and hydroform cavity.
- Figure 1.5.2.17-6 shows possible failures during the deep drawing operation. Figure 1.5.2.17-7 shows possible failures during the hydroforming phase.

Figure 1.5.2.17-6: Deep drawing process limits
The process of conventional deep drawing followed by hydroforming is compared to a stretch forming process ("Hishida" geometry). It is found that deep drawing followed by hydroforming can produce a cavity that is 20% deeper compared to stretch forming.

The use of conventional and hydromechanical deep drawing is investigated for forming fuel tanks from steel. The research is done as a result of stringent hydrocarbon emission regulations.

Currently, around 70% of fuel tanks are manufactured from plastic using extrusion blow molding. However, the plastic does not prevent permeation of hydrocarbons through the tank walls. New processing techniques can reduce the hydrocarbon permeation but are not economical.

As a result, metallic materials are the preferred means for creating an impermeable fuel tank. Stainless steel alloys are of particular interest because they provide adequate strength, formability and corrosion resistance.

Conventional deep drawing, high pressure forming of double blanks and hydromechanical deep drawing are viable manufacturing techniques for production of fuel shells from steel.

The hydromechanical deep drawing process, which allows limiting draw ratios of up to 2.7, is shown in Figure 1.5.2.18-1 below.
Initial research was done to evaluate the possibility of manufacturing a simplified steel fuel tank. The plastic tank was redesigned to provide a flow-oriented geometry (sharp edges reduced and radii enlarged as much as possible). The first steel tank variant is compared to the plastic tank in Figure 1.5.2.18-2.

The fuel tank is split into an upper and lower shell as shown in Figure 1.5.2.18-3. FEM simulations show that the upper shell can be formed using conventional deep drawing but the complex lower shell must be formed via hydromechanical deep drawing.

The upper shell is drawn with conventional deep drawing and is shown in Figure 1.5.2.18-4.
The lower shell is formed hydromechanically and is depicted in Figure 1.5.2.18-5. It was found that the working process window for a good part is very small.

Results of the research show that it is possible to form a relatively complex fuel tank from steel using conventional and hydromechanical deep drawing (see Figure 1.5.2.18-6). Despite an increase in specific weight, the dual shell tank is 20% lighter than the plastic tank due to decreased wall thickness. A further advantage of decreased wall thickness is a 2.8-liter increase in gross fuel capacity.
Impact of new production processes in industry is often much more profound and sweeping than the new products produced by these processes.

Experienced gained from the introduction of a new processes can generate new ideas on how to design new products.

Hydroforming of sheets and double welded blanks allows the use of higher tensile strength steels and aluminum alloys. Process refinement using FEM simulation allows optimization of manufacturing processes.

Laser material processing permits cost-efficient, precise and extremely flexible trimming of hydroformed components.

Presently, hydroforming is concentrated in the automotive industry. Tailored geometries, reduced weight parts and parts from different materials are currently being manufactured.

In the future, hydroforming is expected to open other application areas where high strength-to-weight ratios and economic efficiency are required.

A partnership between industry and scientific institutions is required to develop new processes for the future.

The paper presents numerical and experimental results from a modified hydromechanical deep drawing process in which uniform pressure is generated on the flange. A seal is used to prevent leakage of the fluid from the flange, see Figure 1.5.2.20-1. Therefore, after the initial pressure builds up, the container pressure and the pressure on the flange are equal.

Figure 1.5.2.20-1: Modified hydromechanical deep drawing tooling

Preliminary experimental investigations show that using Al 1050 HO of thickness 1.24 mm, limiting draw ratios (LDR) up to 3 can be attained. Figure 1.5.2.20-2 shows an Al 1050 HO sample with LDR of 2.86. The maximum LDR obtained with conventional deep drawing was 1.8.

Figure 1.5.2.20-2: Cup drawn from Al 1050 HO (draw ratio = 2.86)
Finite element simulations were done to investigate formation of wrinkles in the cup and sensitivity to friction at the blank-blank holder interface.

FEM simulations show that a) the process is very sensitive to friction at the blank-blank holder interface b) container pressure as a function of punch displacement required to avoid contact between the blank and draw die can be determined and c) it is possible to draw the cup without wrinkling in the cup wall.

FEM simulation results were used to conduct experiments for drawing cups from Al 6016. Figure 1.5.2.20-3 shows that a maximum draw ratio of 2.29 could be obtained. Cups with higher draw ratios could not be drawn due to fracture in the cup wall.

Figure 1.5.2.20-3: Drawn cup from Al 6016 (draw ratio = 2.29)

The proposed hydroforming process generates uniform pressure on the cup flange; therefore, the process can easily be simulated with FEM. Using Al 1050 HO, a maximum draw ratio as high as 3.0 could be obtained. However, a maximum draw ratio of only 2.29 could be realized with Al 6016.


The paper discusses several state-of-the-art techniques in sheet metal hydroforming. Processes discussed are a) internal high-pressure forming of double blanks b) combination of deep drawing and internal high pressure forming of double blanks c) hydromechanical deep drawing and d) high-pressure sheet metal forming.

1. Internal high-pressure forming of double blanks

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- This process is used to create complex hollow components in a single tool or a short process chain.
- Basic principle is to introduce a fluid medium between to metal sheets. The sheets are formed into hollow components by pressurizing the fluid. A docking system is required to introduce the medium between the sheets. Example docking systems are depicted in Figure 1.5.2.21-1 below.

![Docking systems](image)

**Figure 1.5.2.21-1: Docking systems used for internal high-pressure forming**

- Sheets must be sealed in the flange area to prevent fluid leakage. This is typically done by a) welding the sheets together at the seams to provide a leak-proof barrier or b) apply a mechanical closing force that generates sufficient contact pressure between the sheets to prevent leakage.
- Welding sheets has the advantage of lowering the closing force, which allows material to flow into the die more easily. A disadvantage of welded sheets is that draw depths between the upper and lower shell must be similar. Figure 1.5.2.21-2 shows the bursting pressure as a function of draw depth ratio for welded and unwelded blanks. The figure shows that larger draw depth ratios can be obtained from unwelded blanks.
Unwelded blanks allow relative sliding between the upper and lower blanks. Therefore, larger draw depth ratios can be obtained as previously discussed. However, a closing force is required to generate sufficient contact pressure between the sheets to prevent leakage of the pressurizing medium.

Finite element simulation is required to determine the process limits for internal high-pressure forming. Using numerical simulation, process limits such as bursting, fracture and wrinkling can be identified and corrected. FEM simulation can be used to determine a) optimum blank geometry b) internal pressure required for final calibration c) retaining forces required to prevent tools from opening and d) friction coefficients required for practical implementation.

A diagram showing the process limits for internal high-pressure forming is shown in Figure 1.5.2.21-3.

Internal high-pressure hydroforming can be used to shorten the process chain thereby reducing the number of tools and machines required. However, the process is only economical in small and medium batch production due to long cycle times.

Internal high-pressure forming produces higher and more uniform strain hardening in the part while allowing for production of components with major changes in cross sections.

2. Combined deep drawing and internal high-pressure forming
A process combining conventional deep drawing with hydroforming of double blanks is shown in Figure 1.5.2.21-4.

Figure 1.5.2.21-4: Combined deep drawing and internal high-pressure forming

- Initially, the two blanks are drawn to a desired depth. Then, a pressurizing medium is introduced between the blanks and a hollow body is formed by internal pressure.

3. Hydromechanical deep drawing
- Provides the following advantages a) high draw ratio in first draw b) complex side wall shapes in first draw c) low inherent stresses d) high shape and dimensional accuracy e) high degree of surface quality f) decrease in wall thinning and g) lower tooling costs.
- The process has substantially slower cycle times.
- “Active Hydro-Mec” process, shown in Figure 1.5.2.21-5, can be used to increase strain hardening in body panels, thereby increasing component stability and dent resistance. Since component stability is increased, thinner sheets can be used for a body panel, which results in weight reduction. A sample engine hood formed by Schuler with the “Active Hydro-Mec” process is shown in Figure 1.5.2.21-6.

Figure 1.5.2.21-5: “Active Hydro-Mec” process
1.5.2.22 “Sheet hydroforming for the automotive industry (Research)”
Prof. M. Geiger – Institute for Manufacturing Science,
University of Erlangen-Nuremberg, Germany.

- Lightweight car body design is required to realize new environmental constraints that require increased fuel efficiencies.
- This project pursues the realization of lightweight designs by the integration of several functions within one highly complex part, which is hydroformed.
- The main focus of the research is on the investigation of counter punch concepts.
- FEM simulations and practical experiments show the influence of different process strategies on the forming potential and the part properties.

1.5.3 Process Variations
1.5.3.1 “Hydroforming with local workpiece heating by laser radiation (Research)” Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

- In hydroforming, small geometrical features require high calibration pressures and a complex forming process.
- Heating by laser radiation can reduce the calibration pressure because a higher material ductility and lower flow stress are available.
The aim of the research is to examine the possibilities of local workpiece heating during the hydroforming process.

The direct heating by laser radiation is studied both numerically with FEM simulation and experimentally.

Conduction of heat as well as changes in material properties is analyzed.

1.5.3.2 “Hydroforming of deep drawn preforms starting from homogenous sheet material possessing locally different flow properties (Research)” Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.


R&D and applications in sheet hydroforming are well known and discussed throughout this report. Nevertheless the technology is being further developed in order to form more complex parts with improved geometric definition and smaller corner radii.

Research is in progress in combining sheet hydroforming with electro hydraulic forming. In this process, a part is first formed by hydroforming at moderate pressures. Subsequently by using an impulse pressure, created by an electro hydraulic technique, it is possible to coin or calibrate the deformed parts to achieve small radii, desired by the designer, Figure 1.5.3.3-1.
Conventional sheet hydroforming uses water with additives as a pressure medium. However, Viscous Pressure Forming (VPF), using a viscous material can also be used in the hydroforming process and offers the advantages of improved sealing to reduce leakage and easier handling in prototype production of a small number of parts.

This paper describes the application of VPF to forming of a non-symmetric part from steel, aluminum and a nickel alloy. FEA simulation and blank holder force control are utilized to optimize process conditions. The effect of process variables upon the achievable part geometry is discussed. Comparison of FEA predictions with experiments illustrated that metal flow and thinning can be estimated with good accuracy.

The influence of various process parameters such as forming speed, clamping load and viscous medium pressure on the final part geometry is discussed.

A series of computer simulations were conducted using the FEM code PAM-STAMP to help design the part and blank geometries. The objective of the simulations was to design the part geometry such that it would be possible to form the part defect free.

Viscous pressure forming was evaluated with numerical simulations and experiments. It was shown that it is possible to form simple parts with a simple tool design using conventional press actions. The ram force and cushion force can be used to generate pressure in the viscous medium while providing sealing.
1.6 Tube Forming (Bending, End Forming and Hydroforming)

1.6.1 Machines


- Several process development possibilities and state of the art press technologies associated with today’s hydroforming lines are discussed.
- In general, reducing cycle time, reducing investment costs, and shortening the process chain can improve the present state of hydroforming.
- Process simulation with FEA is a vital tool in making these improvements.
- Cycle times have been reduced by the following means:
  1. Quick Filling System: a gravity fed system originating from a tank on top of the press fills the tube with the forming medium during tool closing, preforming, sealing, and force application without air locking problems.
  2. Performing the preform operation in the hydroforming tool.
  3. Reducing the filling to forming transition time by using controls and adjustable electronic programs to optimize conditions. This has proven to reduce cycle times by 1.5-2 seconds.
- Double Ram presses reduce investment costs and shorten the process chain by matching the production of two single presses, and providing high flexibility with two separately moving rams.


- The application of a hydraulic system for high pressure internal forming is discussed.
- In order to generate high pressures within a die, a device to close the die and withstand the high forming forces is required. These devices are typically hydraulic units and are based on one of three principles.
Because the hydroformed parts are placed in and removed from the die by hand, the controller for the hydraulic system must guarantee maximum safety.

The hydraulic axial cylinders used to close the tube ends must meet high demands.
1. The mineral oil used in most hydraulic drive units becomes a problem in an open forming circuit because of its flammability.
2. Any hydraulic drive medium for an open forming circuit will be susceptible to contamination from the air.
3. Water, with additives for lubrication and corrosion protection, presents many obstacles to being used as a hydraulic drive medium.

The solution is to use a pressure intensifier to separate the mineral oil hydraulic drive medium from the water-based forming medium.

For pressures up to 2000 bar, the pressure barrel of the pressure intensifier is manufactured as a single-shell unit. For pressures above 2000 bar, the pressure barrel is manufactured as a two-shell unit.
The pressure intensifier can be mounted with the axial cylinders or mounted separately. In addition, it can be mounted with the pressure vessel pointing upwards, downwards, or horizontal.

The water-based forming medium must go through a treatment system in order to remove the contaminants introduced in the forming process.

Manufacturers of Tube Hydroforming presses are continuously developing new press concepts to a) reduce cycle time and capital
investment, and b) increase flexibility and access to die area for improved handling.

- Various new press design concepts are proposed such as: a) two-column press system, Figure 1.6.1.3-1. A 5000 t press of this type will be installed in Canada by July 2002, b) double-ram press system, Figure 1.6.1.3-2 can be operated in single mode (2 rams/different parts) or in coupled mode (2 rams coupled/one part) while only one water pressure system is used. Thus, productivity is increased.

![Two-column press system](image1)

**Figure 1.6.1.3-1: Two-column press system**

![5000 ton double-ram press system](image2)

**Figure 1.6.1.3-2: 5000 ton double-ram press system**


- Extrusions are very important for lightweight constructions as they combine high stiffness and low weight. While the mass production of bent extrusions by means of conventional bending technologies has been developed and perfected over many years, the
The prototyping of such extrusions is still a very time and cost consuming process.

- One prototyping method that has been developed in the last few years is laser bending of extrusions. This process can bend complex extrusions (see Figure 1.6.1.4-1).

![Figure 1.6.1.4-1: Principle of section bending](image)

- The main drawback of this method is the quite low accuracy of the bending process. Therefore a closed loop system for laser bending of extrusions has been developed. It is mainly based on a topometrical 3D sensor that is used to determine the actual geometry of the bent extrusion.
- It combines a technology processor that analyses the extrusion geometry, simulates the forming process and finally generates the NC codes for the machine tool.
- To realize online controlling, only simple areas of interest on the part are digitized with a 3D sensor. According to geometry information the machine tool can be controlled.
- As a wide range of mechanical parts possess regular, simple surfaces, the proposed method could also be used for other forming processes. It can work for all parts where a rep model is available and the forming process can be simulated.


- In manufacturing space-frame structures and for preforming tubes a 3D bending operation may be necessary. A bending machine
that can be programmed for forming each individual part offers considerable flexibility in product development.

- Such a machine, a so-called “Hexabend,” uses the well-known hexapod principle. The machine has six programmable hydraulic cylinders that can move the bending die in 3D space to bend the tubular part (tube or profile) into the desired shape, Figure 1.6.1.5-1.
- The machine is equipped with a heating system to facilitate bending, a measurement and control system to compensate springback, a mandrel and a lubrication system.

![Figure 1.6.1.5-1: Tubular part bent with “Hexabend”](image)

1.6.2 Tools


- Examples of hydroforming process chains capable of producing precision parts are discussed.
- Sheet and tube profiles are produced by chain of processes. The deviations (errors) from each process accumulate.
- In hydroforming, more errors are introduced due to springback, tool wear, and deviation in workpiece properties and process parameters.
- FEA simulations have allowed the technology to be put to use.
- The following approaches are recommended for the future:
  1. As parts become larger, wrinkling must be avoided in prebending and hydroforming.
  2. As parts become larger, closing forces must increase.
  3. As shapes become more complex, expansions as $\Delta d/d_0 > 1$ must be realized.
4. As sheet metal is increasingly hydroformed, a calibration step must be introduced.
5. Friction forces need to be measured and lubrication principles need to be developed.
6. Methods must be developed to allow for wall thickness distribution control.
   - The measured accuracy of a hydroformed subframe proved that precision parts could be formed regardless of the deviations in the raw material.
   - Local heat treatment proved to be an effective method of controlling material flow and thus wall thickness distribution in hydroforming.

1.6.2.2 “Reduction of CO2-impact by weight reduction achieved by bending and hydroforming of steel and aluminum tubular parts for body and chassis applications (Research)” Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

   - The process chain for the production of modern lightweight constructions, which makes high demands on the individual process steps and the used materials, is researched.
   - A kinematic bending process for the 3D-forming of tubes has been developed.
   - Kinematic conditions during forming lead to a higher residual formability, which positively affects the following hydroforming process.

1.6.2.3 Siegert, K., (1999) “Hydroforming of Tubes with External High Pressure” Hydroforming of Tubes, Extrusions and Sheet Metals, Institute for Metal Forming Technology of the University of Stuttgart, Germany, pp. 463-480.

   - The fundamental principles of forming tubes via externally applied pressures are discussed. External high pressure forming (EHF) is the process of forming an internal shape for hollow sections by reducing the cross section over a mandrel.
The following parameters were studied:
1. Materials: AlMgSi1-T4 and CuZn37
2. Tube Geometry: diameter, wall thickness
3. Mandrel Geometry: length of forming zone, number of noses, shoulder angle
4. Process Parameters: pressure, pressure trajectory

In EHF, the tube is plastically deformed in the radial direction while the wall thickness increases as a result of the tangential compressive stresses. However, the compressive stresses may cause buckling of the tube.

FEM simulations were used to predict buckling pressures and shapes.

The FEM results were compared to experiment.

The number of buckles in the circumferential direction depended on forming zone length, outer diameter, and material.

The mandrel shapes were based on the buckling shapes obtained from FEM simulations. It was shown that buckling could be a part the mandrel design process.
The pressure required to form the tube depended on mandrel shape, shoulder radii, and nose depth.

In the future, the integration of tensile and compressive axial forces in the EHF process will be studied.

The fundamentals of hydroforming die design and finishing as well as die tryout are discussed. The advantages of using a cast die body include:
1. Ability to produce near-net-shape parts.
2. Availability.

The disadvantages of using a cast die body include:
1. Reduced load capacity caused by tensile stresses arising from the high calibration forces that exceed the fatigue strength of the material.
2. Difficulty incorporating changes after the die has been cast.

Inserts can be fit into the regions of the cast die body where stresses are high; however, the stress distribution should be studied for the situations where the insert breaks.

The advantages of using a forged die body include:
1. Increased load capacity.
2. Increased flexibility with the die after it has been forged.

Die inserts should be used in the following instances:
1. To reduce stresses in the die block.
2. To increase flexibility with regard to geometry changes, die materials, heat treatment conditions and coatings.
3. To act as ejectors to prevent the part from sticking in the top half of the die.
4. To act as ejectors to lift the part for faster and easier handling out of the lower die.
5. To accommodate piercing bushings.
6. To act as wear inserts for critical wear zones.
7. To help fill parts quickly at high flow rates.

- In order to maximize part accuracy and die life, the contact area between die body and die insert should be maximized.
- A die tryout scheme that has proven itself at Krupp Drauz proceeds as follows:
  1. Calculate the calibration pressure and the pressure causing metal flow under pure internal pressure.
  2. Determine a suitable number of pressure intervals with an appropriate increment.
  3. Determine the maximum axial feeding length in the second pressure interval that will not cause wrinkling.
  4. Determine the minimum axial feeding length in the second pressure interval that will not cause necking.
  5. Develop a parameter curve. The process should proceed between the maximum material input and the minimum material input.


- Design guidelines for aluminum parts and process integration techniques in hydroforming processes are discussed.
- The advantages of beginning the hydroforming process with an aluminum extruded section include:
  1. Varying wall thickness throughout the section.
  2. The use of hollow cavity cross sections.
  3. Freedom in flange design.
  5. Cross section corresponds to final section before calibration.
- The disadvantages of beginning the hydroforming process with an aluminum extruded section include:
  1. Lower ability to reform section.
  2. Lower capacity for flaring.
  3. Greater spring back tendency.
  4. Increased tooling costs.
- Design guidelines for aluminum extruded sections include:
  1. Avoid sharp angles between adjacent walls because they will cause sealing problems.
2. Flanges should be located in the corners in order to incorporate the flange into the tooling.
3. Thicken the walls in the corner regions of the initial section in order to make the wall thickness distribution more uniform in the final section.

- Processes such as punching, flange trimming, and machining of the ends can be integrated into the high pressure forming process.
- Characteristics of punching from the outside inwards include:
  1. Internal pressure independent of hole size.
  2. Hydraulic cylinder proportional to hole size.
  3. Punch plug can be folded over to eliminate its removal.
  4. A certain amount of wall collapse occurs.
  5. Good quality, accuracy, and reproducibility.

![Figure 1.6.2.5-1: Outside inwards punching](image1)

- Characteristics of punching from the inside outwards include:
  1. No wall collapse occurs.
  2. Reproducibility and quality are worse.
  3. Slug disposal can be built into upper tooling, but slows cycle time.

![Figure 1.6.2.5-2: Inside outwards punching](image2)
One axial sealing system for multi-cavity sections was presented.

Figure 1.6.2.5-3: Axial sealing system for multi-cavity sections

1.6.2.6 Flehmig, T., Blumel, K., Kibben, M., “Investigation to Bending Boundaries of Circular Tube Cross Sections” Hydroforming of Tubes, Extrusions and Sheet Metals, Institute for Metal Forming Technology of the University of Stuttgart, Germany, pp. 41-62.

- The bending limits of circular tubes are studied by empirically defining an equation for the bending limits. Also, a simple bending mandrel that can exceed these limits is discussed.
- The bending limits are determined by necking or cracking in the outer bow or buckling in the inner bow.
- One bending limit estimation is based on bending radius, tube diameter, and wall thickness but not on:
  1. Bending angle.
  3. Influence of wiper dies.
  4. Mandrel design.
  5. Friction variations.
  6. Influence of clearance between tube and mandrel shaft.
  7. Non-cylindrical cross sections.
- Starting with the exact analytical solution for the critical buckling stress of a circular shell under axial pressure several factors were empirically introduced in order to account for the previous variations.
- The analytical solution was successfully compared to the FEA solution.
- The requirements of the new mandrel design included:
  1. Rigid and incompressible with a minimal clearance to the tube behind the apex.
  2. Flexible, radially slightly compressible, and able to avoid axial lengthening.
  4. To enable sliding between mandrel and clamping die.
5. To provide sliding between clamping die and mandrel.
6. To minimize or eliminate ovality.
7. To fill the inner cross section at least in the necessary bending angle.

- The characteristics of the new mandrel include:
  1. It shifts the known practical bending boundaries.
  2. After bending, the tubes have more forming reserves on the outer bow. This is important especially in the case of hydroforming.
  3. It gives the tube bows and excellent geometric and optical appearance without ovality.
  4. The use of an integrated clamping plug in the mandrel enables the clamping of very thin walls.
  5. It is much cheaper than other mandrels.
  6. In the case of thick walled tubes, the elastomer life is shorter, but the change time of worn parts is also shorter.

Figure 1.6.2.6-1: Proposed mandrel design


- Rapid and reliable methods for component development and economic manufacturing as related to hydroforming techniques are discussed.
1. FEA is used to:
   1. Check the production feasibility of the component.
   2. Analyze and optimize the final component quality and expected process reliability.
   3. Determine an indication of the required process forces for the die and machine design.

2. In order to obtain reliable FEA results, the tube should be modeled as it passes through all forming processes so that the stresses and strains from the previous step are accurate.

3. Hydroforming cycle times can be improved as follows:
   1. Decrease the fluid filling time of the workpiece.
   2. Fast transition from filling to forming by regulating the high-pressure intensifier and axial cylinder speed with special controls and electronic programs.
   3. Increase forming speed.
   4. Reduce subsidiary operation times.

4. Double ram presses offer more flexibility in the process chain.


5. Extruded aluminum profiles are important structural elements in lightweight construction of the space frame body and in the railway sector. Because of subsequent assembly processes like welding, the demand on the quality of the section increases.

6. Existing bending processes have been modified and new processes have been developed in order to optimize the bending of profiles by means of increasing flexibility and combining the advantages of different bending processes.

7. Based on finite element simulations and semi-analytic process simulations, a new method has been developed that generates more accurate data for a numerical control.
The quality of the process simulation increases with the number of parameters taken into account (see Figure 1.6.2.8-1). Based on input data, the curvature and bending moment of the loaded profile are calculated. The calculated values are then used to determine the curvature of the unloaded profile and required adjustments of the bending rolls in an iterative way. Thus, use of these simulations in combination with an online measurement system, which measures the actual curvature, allows for an increase in bending accuracy. The formability of rounded profiles also increases as a result of subsequent forming processes such as internal high-pressure forming.


- The formation of an analytical tube hydroforming model from plasticity, membrane and thin-thick walled tube theories is discussed.
- The limitations or failure modes in tube hydroforming can be grouped as follows:
  1. Wrinkling
  2. Buckling
  3. Bursting
- The prediction of tube buckling was based on Euler’s column buckling equation, but instead of being dependent on the material’s elastic modulus, it was dependent on the tangent modulus (the slope of the flow stress curve in the plastic range).
• The prediction of tube wrinkling was based on Timoshenko’s theoretical equation, but once again, the elastic modulus was replaced by the tangent modulus.
• The prediction of bursting was based on membrane analogy. It concluded that bursting would occur if the sum of the axial and hoop strain reached the value of the strain hardening coefficient.
• The loading paths in a tube hydroforming process, i.e. internal pressure vs. time and axial feed vs. time, must all work together in order to form a successful part. As a theoretical approach to solving this problem, each parameter was studied.
• Membrane analogy was able to predict bursting pressures that agreed very well with experimental results.
• Thick walled tube theory was able to predict calibrating pressures that agreed very well with experimental results.
• Theoretical prediction of the required axial force in an axisymmetric bulge part did not agree with experimental results as well as previous cases. Inaccuracies in material properties or friction values could have been to blame.
• Using force equilibrium, a theoretical counter force was predicted that agreed very well with FEA results.
• Membrane analogy was used to predict the final wall thickness distribution in a bulged tubular section.
• Having studied all of the individual parameters, a program was written to determine the minimum and maximum pressure vs. axial force curves for an axisymmetric bulged part. Comparison with experimental results showed sufficient accuracy, with deviations attributed to inaccuracies in material properties and friction values.
• It was concluded that the models will not be very useful to designers of more complex geometries, but they should provide some intuition during the early stages of design work.

1.6.3 Process Variations


• Similar to forming tailored welded blanks, tailored welded tubes can also be used for producing tubular products, Figure 1.6.3.1-1, with varying material and/or wall thickness in the axial direction.
R&D on this technology is being conducted in the U.S. as well as in Germany. Different material properties and wall thickness in the tubular preform require innovative methods for producing defect free components.

The present practical use of this technology appears to be limited. Nevertheless, potential applications exist and with increasing acceptance of tube hydroforming in general, forming of tailored tubes will certainly increase.
2. Billet and Rod Forming Machines and Tooling

2.1 Wire and Rod Drawing, Forming and Shearing

2.1.1 Machines


- Sections are conventionally produced with a consecutive set consisting of breakdown mill, roughing mills and finishing mill. These mills in which universal rolls or grooved rolls are adopted, have fixed roll dimensions so that it is necessary to change rolls when dimensions of product are changed. Hence, the process lacks flexibility.

- In order to make production flexible without degradation of productivity, a Skewed Roll Mill (SKM) is developed (see Figure 2.1.1.1-1). It is installed between the roughing mill and the finishing mill.

- SKM consists of two stands so that it is possible to change distance L (distance between rolls) flexibly by setting each position. The axis of the roll, which is vertically inclined by angle $\beta$, is fixed. It is also inclined in the rolling direction by a cross-angle $\alpha$ and can be changed from 0 to 10 degrees.

![Figure 2.1.1.1-1: Shape of SKM](image)

- Since SKM functions for partial reduction, expanding and bending, it can be used as a pre-forming mill. To apply these functions, the flexible size rolling technology is successfully realized with SKM.

- The SKM is employed for expanding web height of H beams flexibly, and forming flanges of H beams into tubular shape. H beams with fixed outside web dimensions are produced with different standards BS, ASTM, JIS, etc.

- By bending of flanges of H beam, a new type of section e.g. steel diaphragm walls is produced without grooved rolls.
• Hence not only the flexibility of the process is increased, the productivity is increased too.

2.1.2 Tools

2.1.3 Process Variations


• High viscosity lubricants containing chlorine and high-pressure additives cause difficulty in degreasing and final disposal of lubricants.
• In order to solve this problem, a wire drawing method is suggested in this study in which ultrasonic vibration is applied to a die so that it can be vibrated radially.
• The effects of applying transverse or radial ultrasonic vibration (RVD operation) on dies are investigated and compared with the effects of applying axial ultrasonic vibration (AVD operation) and those of conventional wire drawing operation without applying vibrations (CD operation).
• Various lubricants are used and comprehensive evaluation of surface condition of the drawn rods and drawing forces is done.
• It was seen that drawing forces are 10-15% lower in RVD as compared to AVD and CD operations. In RVD operation, dull surface of the drawn wire was maintained up to 85% of the critical speed (55m/min), which indicates good lubrication conditions and increase in drawing speed.
• RVD operation realized the skin pass drawing of stainless steel wires with the use of chlorine free lubricants and/or lubricants with low viscosity as compared with RVD and CD operations.
• RVD operation also improved the critical drawing speed by about 10 times that in an AVD operation.


• A major problem of conventional wire and tube drawing introduction of high forces into the forming area. Compared to the conventional method, the forming process limits can be extended by superimposing ultrasonic waves due to decreasing drawing forces.
• Different techniques can be used to excite the die. One possibility is the variation of the vibration mode. If the vibration direction is
parallel to the direction of drawing, the main influence is on the friction between the workpiece and the die.

- This paper shows that the reduction of sliding friction between a longitudinal oscillating die and the workpiece can be explained by the so-called Sliding Friction Vector Effect.

![Diagram of Die Mounting and Oscillation System]

**Figure 2.1.3.2-1: Die Mounting and Oscillation System**

- A statistical measurement of roughness is made to show the effect of ultrasonic vibration on friction and the results are compared with wire and tube drawing experiments with copper and Ti alloys.
- As shown by experimental investigations, the application of ultrasonic oscillations for metal forming processes results in
  1. Reduction of forming forces.
  2. Reduction in flow stress.
  3. Reduction of the friction between the die and workpiece.
  4. Increased surface quality and higher form precision.
- With increasing drawing velocities, the drawing force reductions are small.
- The reduction in drawing force and surface quality depends on the amplitude of vibration.

2.1.3.3 Altan, T. (2001), "High Speed or Adiabatic Shearing Technology" review prepared by ERC/NSM.

- High velocity shearing from rod or wire is known to produce good surface quality with little or no burrs. The process is sometimes called "adiabatic shearing" because the heat generated at the shear zone remains there and there is no time for heat conduction.
- Various companies offer high speed or impact shearing machines, for example: a) Exotec Impact Technology (exotec@alfa.telenordia.se), b) LMC, Inc. (lmcpress.com), c) Hydropulsor, d) Nikom, e) Truckma, f) Lourdes and g) Aida.
- R&D is being conducted at two Fraunhofer Institutes (IWV-Chemnitz and TEG-Stuttgart) to expand the capabilities of high speed shearing.

2.1.3.4 “Manufacturing of Internal Gear Teeth using a Combined Rolling / Ironing Process (Research)” Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

- To a very large extent, internal gears are manufactured by machining, i.e. hobbing or milling. The machining process is time consuming and costly.
- The objective is to develop a method for forming the internal gear teeth such that no subsequent machining and finishing of the gear surfaces are required while only the OD of the part will be machined.
- To manufacture the cup-shaped component the so-called multiple-roll forming principle is used. After each operation (roll forming, machining and heat treatment) die dimensions are determined. The quality of the gear teeth is evaluated regarding tooth root strength and flank surface hardness. FEM simulation is used to facilitate the process and tool development. An economic evaluation is made to compare the manufacturing costs of the present method with that of machining.

Figure 2.1.3.4-1: Gear teeth manufacture using combined rolling/ironing

2.2 Cold and Warm Forging and Extrusion

2.2.1 Machines


- A new generation of vertical presses for cold and warm forming, designed by Schuler Pressen GmbH & Co. KG, is introduced. The
presses are designed in a modular way with new drive characteristics, which combine the benefits of modified knuckle joint and eccentric drive presses. The presses offer higher flexibility at reasonable costs.

- Schuler determined the following as basic customer needs, a) shorter delivery time b) reasonable investment cost and c) presses designed to the part range they need to produce. A modular press design allows different technical characteristics to be achieved while changing only a few well-defined elements of the basic press design.

- Schuler grouped the parts produced by cold and warm forming into the following categories a) electrical components for the automotive industry (alternator poles with and without core, poleshoes, sleeves, tappets, starters) b) gear box components (differential bevel gears, synchron rings, gear blanks) c) c.v. joint parts d) shaft parts and e) steering and wheel connection parts (tie rod ends, inner races, flange housings).

- The above part categories determine press characteristics such as total force, forming energy, nominal force travel, press stroke, table and slide size, etc.

- Press forces of 3,000 to 16,000 kN are found to be sufficient, with bigger shaft parts requiring press forces up 20,000 kN. Weight reduction in auto components leads to smaller wall thickness, which results in higher press forces. Also, near net-shape production leads to tighter tolerances and higher press forces.

- A new drive with characteristics similar to eccentric and modified knuckle joint drives is developed. The forming velocities for presses using this new drive with strokes of 400, 500 and 630 mm are compared to an eccentric and modified knuckle joint drive with 400 mm stroke in Figure 2.2.1.1-1. The new drive concept combines the advantages of both modified knuckle joint and eccentric drives.
Figure 2.2.1.1-1: Comparison of new drive to eccentric and modified knuckle joint


- This paper discusses the work of Aida Engineering in the field of small cold forging and Flow control forming.
- Flow control forming combines traditional cold forging and sheet metal working. Two families of machines have been developed which have features particularly suited to this field of manufacture.
- The multi slide machines have separate slides driven from one crank while servo controlled machines use either direct linear or screw drive to actuate the slide.
- Special features of the servo presses are:
  1. Accurate bottom dead center positioning allows the potential to perform operations more precisely.
  2. Fully programmable motion, velocity, acceleration, dwell, etc.
  3. Reduced impact and noise.
  4. Full force available over the entire machine stroke unlike a conventional mechanical press where torque and rating point are limiting factors.
Multi slide machines provide the possibility of accurate forming of pre-forms and final forms by isolating the influence of one stage over the next. Its advantages are as follows:
1. Each ram can be adjusted individually and any change in load cannot affect the penetration of the adjacent ram due to time phasing.
2. Since the rams transmit their load to the frame at different times, the frame can be made physically smaller.

Both the servo and multi slide presses enable the introduction of feed forward control. In feed forward control, parameters of the input material and dies are measured. This information is used to adjust the press before a part is made.

Flow control forming provides an alternative to conventional bulk forming which in some cases offer more economical production route.


An increasing number of precision hot forging applications in the automotive industry have shown the limitations of conventional forging machines.

Particularly for requirements such as reliable closing of dies, short deformation times, constant energy distribution, overload protection, and process integrated quality control, new concepts in hot forging machines are continually being developed.

This paper introduces a mechanical press with non-circular gears in the press drive mechanism realizing an optimized slide-stroke-time behavior.
To avoid thermal damage to the die, heat transfer from the workpiece to the die should be the minimum that can be achieved by shorter pressure dwells using fast forging machines.

An innovative concept is used to achieve this. It consists of a mechanical press with non-circular gears in the drive mechanism. A circular gear is used to drive a non-circular gear, which in turn controls the ram movement as shown in Figure 2.2.1.3-1

![Press concept with non-circular gear](image)

**Figure 2.2.1.3-1: Press concept with non-circular gear**

- Another feature is the integrated closing device that separates the two actions a) closing of the die and b) deformation of part.
- It consists of a movable toothed die closed by punch. Columns guide the die with cup spring assemblies providing the die movement and the necessary closing force.
- The basic idea is that the die is closed with a definite closing energy concluding with both the die halves and thus maintaining closing pressure.
- The experimental results and comparison with the conventional process states that the dwell time is reduced by 70% thus increasing the stroke frequency by 1.5 times.
- Press integrated sensors relay information about the process behavior and allow the control of press actions and provide overload protection and thus guarantees 100% quality documentation of the forged parts and avoidance of additional measurement steps.

The ability to form metal parts to net shapes has received increased emphasis in recent years. Globalization, substitute materials, competing technologies and constant pressure to reduce cost are among factors shaping this environment.

Net shape / near net shape forming is associated with reduction in secondary operations. The tighter tolerances often involved demand improvements in process consistency, may require custom machinery, and usually entail greater development time to perfect the process.

This paper stresses that the element of balance forms an important strategic element in implementing advanced technologies in these areas.

The planning half of the equation is concentrated in the engineering design of the process. Execution of the design happens on the shop floor in the production process. Technology used for modeling the process should be balanced with technology for controlling the process.

The technologies the design engineer must consider in developing a net shape forming process include:
1. Analysis of materials for formability.
2. Design of forming tools.
3. Tool material finishes and coatings.
4. Lubrication.
5. Transfer analysis to determine the feasibility of controlling the formed blank.

Various case studies are explained that demonstrate how an effective process design combines computer simulation with machine features to shrink development time. The examples include remodeled processes for manufacturing clinch nuts, spoke nipples, chain bushings, shoes used in car air conditioners, etc.

Today larger parts can be cold formed with greater efficiency and process control needed to achieve net shape.


Complex geometries have been produced for centuries by manual profiling of workpiece materials and using tools with very simple profiles.

The process known as open die forging has been traditionally used in which, the tools are small compared to overall size of the workpiece. Hence, small force is required to plastically deform the material.
This paper presents a new online computer control set up for automation of open die forging.

The overall strategy to produce a required profile is implemented using a one step increment that is repeated several times. Despite that the forming sequence may include the use of different tools, with which the variation in the required force between steps is very small. This offers substantial benefits with respect to material utilization and cost of production.

The current technological advances in analysis, control and electronics can facilitate the development of new operating environments for open die forging which will increase its competitiveness in the global market.

Deformation based analysis is used in the implementation of the required number of incremental steps, movement of tools and manipulation of workpiece material.

The sequence of operation and computer aided process planning for the production of features are provided by an upper bound analysis.

A hydraulic robot, in conjunction with open die forging press furnaces and gripping tools, has been used to build a flexible manufacturing cell. Also, a new hydraulic press has been designed. The press is fully integrated with a tool manipulator and universal tool holder, where all movements are controlled by a PC interface.

The selection of the optimum forming process and route of production are very important for small batch forging. Flat and semi-cylindrical tools were used in this investigation and a near net shape connecting rod was produced.

2.2.2 Tools


During warm forging, lubrication forms a particularly important role and is one of the decisive factors for success of the operations. Oil
graphite emulsions or water-graphite suspensions are often used as lubricants. However, the use of these lubricants is under increasing pressure because of environmental concern and health and safety regulations.

- The European Community has funded a Brite-Euram industrial research project on the development of environmentally friendly tool lubricating systems for the warm forging of steel.
- The development of die lubricants has been accomplished by using spike and friction tests. The spike test represents a combination between upsetting and solid forward extrusion. A mechanical press and 2 dynamometers with the lubricating setup were used for the spike tests. A friction tester was used to carry out the friction tests.
- Various lubricants and their variations were tried and evaluated for the following criteria:
  - For a slug coating and die lubricant:
    1. Easy application and uniform wetting of the slug.
    2. Good adherence to the slug.
    3. Good temperature resistance
    4. Good lubricating properties during forging operation.
    5. Easy application and uniform wetting of the slug.
    6. Good adherence to the slug.
    7. Good release properties
    8. Low impact on environment.
- The slug coatings were divided as graphite based or graphite free.
- The die lubricants were classified as oil graphite based, graphite based and synthetic oil based.
- The experiments show that the selection of die lubricant and slug coatings for warm forging cannot be considered in isolation and should be considered as a package.
- The best results concerning environmental impact and tool life were obtained using a tool lubricating system consisting of graphite based slug coating and oil-graphite free die lubricant.


- The demand of the market to the major industrial cold forgers for the development and production of complicated net shape parts at fairly low unit costs requires innovative new die designs for the optimization of die deflections.
- The strip-wound containers are unique tool elements replacing conventional multiple stress ring sets in tools for cold forging.
They are manufactured by winding a thin strip of high strength steel around a core of tool steel or tungsten carbide. During winding, the strip is loaded with a pre-controlled winding tension.

A comparative study was made between the conventional double stress ring set and the STRECON E containers. A cold forging die for the production of bevel gears is mounted between the 3 containers and analyzed for stress-strain level and accumulated plastic work.

FEM simulations were run to determine the effects of die deflection due to fatigue loading.

The high-stiffness STRECON® $E^+$ containers influence the stresses, strains, and deflections in critical dies so that die life can be improved by factors of 3–10 and die deflections reduced by 30–50%.

It is also possible to create variable internal diameter dies with the STRECON VARY-FIT container.


Friction is a basic factor of the boundary condition and plays a major role in extrusion and affects not only the energy consumption but also the deformation parameters.

It is therefore rational to use friction to assist metal flow. The appropriate use of friction in practice necessitates the solving of complex engineering problems.

Several new technologies are described in the paper:
1. Active-indirect hot extrusion forging in moving container die.
2. Active-indirect hot extrusion forging in stationary container die.
3. Active-indirect hot extrusion with advanced movement of a container.
4. Cold active-indirect extrusion with advanced lubricant in a container and die.

Various experiments are run using an extrusion press with moving and stationary dies.

Units that would have to be reconstructed to make the transfer from conventional processes to active indirect extrusion processes are obtained.

It was found that the processes permit not only cheaper production of exact standard shapes, but also the production of new extrusions and shapes with uniform mechanical properties.

The main advantages of active friction include controlling the distribution of deformation, increasing or decreasing the shear component of deformation as necessary and using the bulk effect of plastic deformation thus improving production rates and costs.

- The early valve body was made up of cast steel. However, valve leakage and machine idling were found because of casting defects. Hence, forging was used to replace the cast steel body. Due to the lack of heavy duty multi cored forging presses, it is difficult to produce these valves.
- It is focused on the metal plastic forming of large-scale cut-off valve bodies used by power plant boilers, and based upon a deep study of combined backward cup–forward rod extrusion.
- This paper presents a new forming process named “shear-extrusion”, of which the main characteristic is that it is labor saving.
- The new shear-extrusion process was studied by methods of numerical analysis and simulating experiment, and the optimal process variables to be applied in the forming of valve bodies were obtained.
- Experiments were run to determine the deformation patterns, distribution of the mean stress field between the 2 processes and using different billet geometries. Simulations were run for the same using DEFORM 3D.
- In order to clarify the labor saving feature of this process, a comparative study was made between lateral extrusion with branches and shear extrusion of a valve body. It can be seen from the results that extrusion force in shear extrusion is about one third that of lateral extrusion.
- Finally, large-scale cut-off valve bodies were formed successfully using a 10,000kN screw press. The new process can be applied to produce not only cut-off valve bodies but also components with branches such as sluice valve bodies, tee-junctions and so on using a smaller forging machine.


- Modern manufacturing technologies demand components produced to very narrow tolerances. In order to fulfill these preconditions, the forming processes must be well understood and kept under permanent control.
- The geometrical accuracy of cold-formed components depends on many parameters, among which the most important are:
  1. Input material
This paper first discusses some efforts in analyzing the impacts of different process parameters where a combination of experiments and numerical evaluations were used.

The research was oriented towards ranking of the parameters, according to their influence and studying their interrelated effects on the processes.

The accuracy of the cold forging process is divided into:
1. Preparatory phase
2. Production/exploitation phase.

In the final sections, an interesting phenomenon concerning the accuracy control was presented. It is possible to find such a combination of parameters where the process is stable, and not so sensitive to the fluctuations of parameters.

The definition of such “stable technological windows” will be very valuable for practice, especially for technology planning.


Outline of an enclosed die forging equipment is introduced first.
Reduction of costs for relatively simple parts was achieved by replacing the conventional machining operations by cold forging.

The state-of-the-art of the cold forging of the steel and aluminum products is reviewed.
Recently used net shape forging technology is applied to warm and cold forging.
The possibility of enclosed die forging is discussed.


Fastener components, traditionally produced (fully or partially) using metal removal processes, are increasingly manufactured by precision cold forming (forging) using multi-station forging (heading machines).
This trend is facilitated by improvements in material quality and surface coating (lubrication) as well as innovations in forming sequence and tool design.
Process simulation using computer software (DEFORM) makes it possible to try out several alternative designs quickly before manufacturing the dies, thus saving time and money.
• Machines used for precision forming parts in large quantities (50 to 200 per minute) have several die stations, “on the fly” computer controlled adjustment of the feed length, kick out and heading edge adjustments, automatic pick-move-place transfer, and precision “zero-clearance” heading slide guiding system. They can also be equipped with an integrated wire drawer and programmable tool changer.


• Increasing production quantities in the automotive industry and the tendency of automotive manufacturers to rely more and more on suppliers results in a distinctive increase in demand for extruded parts.
• Hence, a need for alternatives in the manufacturing process was felt. This paper presents an alternative considered by Schuler Press Company in meeting this demand.
• One alternative is the application of multi-station mechanical presses with modified knuckle joint drives having a stroke of approximately 400 mm.
• Therefore, a multi-station mechanical press system consisting of a feed device for raw material, elevator, automatic weighing unit and feeding parts into the loading station was built.
• As the tool life differs in the workstation, tool changes would be required during the production of one part batch. Here the individual tool change offers a big advantage.
For shaft production at continuous runs exceeding approximately 14-15 strokes per minute (SPM), dry lubrication is not sufficient. As a result, a special lubrication device is designed with a capacity of 50 SPM.

In spite of the progress in tool technology, not all shaft components can be manufactured in one press run. Shafts with undercuts are produced in a different operation.

Maximum possible production numbers of shaft components largely depend on external factors. Hence, a close cooperation with system suppliers in improvement in the limitations is stressed.


Within the scope of the entire car industry, lightweight construction plays an important role in fulfilling requirements from a technological, energetic and economic point of view.

This direction is mainly focused on components that can be produced at optimal weight. The manufacturers seek new, more efficient techniques to manufacture shaft like components with less effort than before.
This paper is based on analyzing the worldwide demand for gear shafts required by the car industry. Possible development trends are discussed. Research projects offering new possibilities for the manufacture of hollow shafts are introduced.

A great potential for innovation in near net shape manufacturing of car components, especially in the range of bulk metal forming is available. Partial forming techniques and combinations of manufacturing techniques, with rotating main movement could provide an efficient solution.

For automotive gear shafts, hollow shafts are used for mass reductions. For strength considerations, the polar moment of inertia of the hollow shaft is about 10% of solid shaft. This results in about 30% material savings.

The following requirements are to be fulfilled for the construction and manufacture:
1. Different wall thickness values of the shaft according to use as loose or fixed gear shaft.
2. Differing wall thickness along the shaft length.
3. Diminution of shaft diameter to the outside toward the bearing positions.
4. Minimal wall thickness values of the fixed gear shafts from 6 to 8 mm.
5. Concentricity of inner to outer contour less than 0.3 mm.

In the production of hollow shafts, the inner contour has to be constructed in a way to be realized by chipless shaping techniques. Here forming techniques should be applied according to appropriate material utilization, short manufacturing times, and high obtainable strength values.

New possibilities in hollow shaft production are opened up by the cross rolling and spin extrusion techniques. Spin extrusion is rotary forming under pressure to produce axisymmetric hollow parts from semi-finished bulk materials or prefabricated solids.

![Figure 2.2.2.9-1: Process chains used to manufacture hollow shafts](image-url)
This paper describes and defines rotary forging while explaining the characteristics that make it an incremental deformation process. Developments leading to the mainstream types of rotary forging systems are discussed and classified.

Important commercial considerations concerning take-up and development of the process are presented together with current successful applications. Market requirements for future process exploitation are described and supported by examples of potential new applications for commercial development and exploitations.

In a rotary forging process, two in line opposing rotating dies are used which can be moved axially to cause deformations whilst one of the dies can have its axis changed with respect to the other that contains the workpiece.

All rotary forging machines can be expressed using Euler angles of nutation, precession and spin. There are various kinds of machines using varying angles.

Rotary forging machines with different genuine ideas were manufactured across the globe by companies such as Slick, Wagoner Banning, Sumitomo, Nottingham, etc.

The incremental nature of the rotary forging process means that the primary deformation zone is continuously moving. This means that secondary deformation zones that exist are also continuously varying.
• A major problem with flashless rotary forging is material entrapment, which often leads to cyclic fatigue damage inside a complex die and inevitable premature tool failure. This also often leads to inaccuracy of dimensional and geometric tolerances.
• The possibility of manufacturing products using flexible batch manufacturing from powder metallurgy process is discussed in the end.


• This paper presents an integrated tool design and manufacturing system for the cold forging of nuts.
• The process adopted in a nut forging includes hexagonal closed die forging, backward extrusion, combined forward and backward extrusion and butt punching. Shapes of the die cavity are constrained by the product profiles. However, the punch profiles can be designed freely to obtain a better tool and die life.
• A CSG solid modeling kernel has been established to integrate the CAD/CAM/CAE functions and help the engineer to design and manufacture the punches.
• The upper bound analysis method was adopted to simulate the forging process and predict the punch load. Upsetting, closed die forging and combined forward and backward extrusion processes were considered in the analysis modules.
• Punch design is done in collaboration with displacement adjustment of the forging machine to average the punch loads. The butt ratio was also considered to achieve both the requirements of material utilization and load limit of tools.
• The forging load of each punch and the velocity field are discussed to explain the design philosophy.
• The system is established using C language and is installed on a WINDOWS PC platform. The results obtained are compared with experimental results. The extrusion load and area reduction of experiment and theory are in good agreement.
• The demonstrated example shows that the same tool with different adjustments can improve the loading condition of the tool.


• Coating technology has led to improved wear resistance in cold forging dies. However, the coating also affects the surface topography, the residual stress distribution, and the microstructure. Thus, it affects crack initiation and fatigue strength. Increasing tool life by considering both wear resistance and fatigue strength is discussed.

• The fatigue strength of coated tool steels were evaluated with a three point bend test under an oscillating load. D2 and M2 tool steel, cylindrical and rectangular cross sections, with and without a notch were tested with various coatings.

• For surface roughness > 2 \( \mu \)m, the fatigue strength was reduced. In PVD coatings, the change in surface roughness is negligible, while in CVD coatings, the change is much higher.

• In about 40% of the PVD coated cylindrical samples, the substrate properties were responsible for fatigue fracture.

• Within PVD and CVD coatings, the kind of coating material does not influence the fatigue strength a great deal.

• The fatigue life of CVD coated tool steels is less than that of non-coated or PVD coated tool steels.
The rectangular samples showed increased crack sensitivity in the edges.

Micro-blasting, which generates a compressive residual stress in the substrate, and duplex coating, which combines plasma nitriding and PVD coating to increase the substrate hardness, can help obtain increased tool life.

Tool life monitoring in production verified that the combination of micro-blasting and duplex coating could increase tool life by increasing both wear resistance and fatigue strength.

2.2.2.13 "Development of a system for the load oriented design and evaluation of tool systems for bulk metal forming (Research)"
Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

Process reliability in cold forging is mainly affected by the quality of the applied tool system.

A primary aim of the research is to increase the service life of dies and cemented carbide inserts for the manufacturing of spheres for ball bearings.

Use of numerical process simulation enables the judgment of design modifications and ensures a shorter development time.

An ultrasonic measurement system is developed, which enables an assessment of the prestressing conditions of the assembled tool system.

2.2.2.14 "Improvement of service life and reliability of cold forging tools with respect to fatigue damage due to cyclic plasticity (Research)"
Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

The main objective is to develop a methodology to increase tool service life.

One part of the research is to develop a technique for the identification of primary parameters that determine the reliability of a tooling system.

Approach lies on dynamic interference analysis, which allows an estimation of failure probability from statistical distributions of strength and load.

Accurate data concerning these statistical distributions will require the collection of information from industrial production.

2.2.2.15 "Fundamental process knowledge of warm forming of shaft-shaped workpieces with overhanging geometrical elements (Research)"
Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.
The lateral extrusion will be used for testing the different shaft-shaped workpieces with overhanging geometrical elements.

A thermal and mechanical analysis of the workpiece and tools is realized with FEM simulations.

The global consideration of process effects and the application of FEM simulation lead to basic process knowledge for the warm forming of steel.


Cold forging of relatively complex shapes, such as bevel gears, inner races for constant velocity joints and trunnions with three or four legs, is state of the art. In such applications multiple-action mechanical/hydraulic die sets are used in vertical mechanical presses. After the dies are closed, punches from top and bottom are actuated to extrude the billet material laterally to precision form the complex part.

Manufacturing of thin walled T-shapes is achieved by tube hydroforming. However, T-shapes with thick walls can only be manufactured by a) stamping and welding, b) cold forming of the two components that are then welded, or c) cold forging in multiple steps with in-between annealing. All these methods are relatively costly.

R&D work is in progress to expand the capabilities of multiple-action tooling to manufacture parts with ever increasing complexity. A new cold forging technique uses a) sheared billet, b) phosphating and lubrication and c) cold forging that consists of lateral forging, backward cup extrusion (twice) and flange upsetting, Figure 2.2.2.16-1.

Figure 2.2.2.16-1: Cold forging of T-shaped parts

• Small metallic parts like contact pins are needed in large numbers in the field of electronics (micro mechanics and micro systems technology).
• The extrusion process is investigated as a means of forming axisymmetric microparts.
• Main focus is on miniaturization effects in frictional behavior and their influence on the extrusion process.
• The influences of specimen size and microstructure on process forces, forming behavior and hardness distribution are investigated.
• Additional friction tests and rod extrusion experiments take into account the influence of surface quality, forming speed and lubricant on miniaturization effects.
• Results show that an effective process design can only be realized when various miniaturization effects are considered.

2.2.2.18 "Warm forming to improve the formability in the field of micro forming (Research)" Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

• Using a warm forming process can extend the formability of parts while leading to a decrease in the required number of process steps. This is particularly important in micro forming processes.
• Expected improvements caused by increased temperature in micro forming are lower yield stress, homogeneous distribution of hardness and deformation, smaller component damage and high surface quality.
• All of the above mentioned effects were verified for experiments using CuZn15, which is an important material for the electronics industry.
• Future investigations will evaluate these results with statistical methods.
• Further investigations will be carried out with X4CrNi18-10, which is an important material for medicine and precision engineering.


• High costs arise in premature tool failure due to cost of replacing the tools, cost of machine downtime, cost of pre and post operative handling and assembly. It has been found that tooling costs can consume 5 to 30% of the manufacturing cost of producing a part.
Hence selection of tool materials and die design may be a limiting factor for the success of a cold heading sequence.

- This article introduces two case studies on improving tool life of cold heading tooling. A method for finding and solving the problem of premature tool failure has been given.
- Designs were analyzed and tested using FEM and then used in actual heading machines where FEM predicted results were obtained.
- A knockout pin that was used to indent a hole on the bottom of a work piece is analyzed. The stress analysis of the pin found tensile stresses of about 60 ksi at the point of failure, which are not high enough for causing plastic deformation, but poor polishing may increase the chances of stress concentration.
- Two alternative designs were analyzed and the stress analysis was performed. A spacer was added at the bottom of the pin, which reduced the stress concentration. The redesign resulted in the insert lasting for 200,000 parts instead of 53,000 for the original case. This resulted in cost savings of about US $19,000 annually.
- Another carbide tool was studied that is located in second die of a cold header. It was seen that the contact forces were producing a bending effect on the insert and created tensile stresses at the point of failure.
- The best alternative suggested and analyzed was to simply provide a relief on the OD to obtain more interference in the middle of the insert that counteracted the bending forces. The tool life was increased to 460,000 parts from 50,000 parts thus resulting in savings of almost US $14,000 annually.
- This paper shows that substantial cost savings can be obtained with a moderate increase in tool life. Also the increase in tool life increases machine efficiencies, lower the amount of scrap parts and decrease problems caused by carry over of failure.

2.2.3 Process Variations

2.3 Hot Forging and Extrusion

2.3.1 Machines


- It is difficult to secure economical efficiency in small-tonnage metallurgical production by means of the employment of traditional technological schemes
The problem of a detailed study of the thermo mechanical features of radial reduction is associated with the new technological processes of the direct combination of continuous casting and forming of metals and alloys.

If the heat of the casting operation is used for the following hot working, the production of metal products can be made economical for comparatively small volumes of production (thousand tons year). Throughput forging is one of few processes that can be simply combined with both horizontal continuous casting and subsequent rolling.

The deformation process of cylindrical billet is divided into 2 stages:
1. Clamping and deformation up to filling of the die space.
2. Deformation when the die gaps are completely filled by the metal.

The analysis of multi-die radial forging is presented by approximate equations of equilibrium and state of plasticity.

Comparative analysis of energy consumption of known processes of metal forming such as extrusion and rolling is carried out to gather the advantages for this process.

Forging leads to over consumption of energy. The best course suggested is to decrease the single reductions. It is concluded that throughput radial forging is the best method for continuous cast billet. Insufficient ductility of the cast metal and temperature gradient do not affect the success of plastic working.

2.3.1.2 “Double Acting High Speed Hot and Warm Forging Press” SMS-Eumuco, Leverhusen, Germany (Product).

Double or triple action press or tooling motions are well known in the cold forging industry. This multiple action design allows the production of complex components to precision tolerances. Examples are bevel gears with teeth, trunnions, CVD inner races, etc.

A press for hot and warm forging of complex parts has been developed and is shown in Figure 2.3.1.2-1. This press has two rams, one moving inside the other. Both rams are driven by one central crankshaft a) the exterior ram by two knuckle joints with horizontal connecting rods providing a slow motion and dwell at bottom dead center b) the interior ram by a crank mechanism with a vertical connecting rod and a fast motion at bottom dead center.

The press can be provided by automation and is already in production. Parts are forged without flash. The exterior ram provides die closure while a punch attached to the interior ram penetrates into the die and deforms the workpiece material to fill the die cavity.
As the necessity for high production and high quality forged parts increased, the presses which had once been applied to only a limited range of products have been superceded by systems which are appropriate for very different forming procedures.

This paper is produced by the closed-die forging division of SMS Eumuco GmBH. It enlists the technical requirements for fully automatic presses regarding their flexible use and the improvements they have achieved in their latest warm and hot forging presses.

The reachable and reproducible precision of a forging manufactured on an eccentric press or wedge press essentially depends on the stiffness behavior of the die machine system.

Presses with monobloc design having high frame stiffness, large pitman distance and minimized ram tilting meet with this requirement.

A patented electro-hydraulic brake system has been developed by SMS that is arranged directly without the gear so that the torsional rigidity as well as engagement safety is improved.
- The clutch is engaged via an annular piston and disengaged by means of a spring system. A closed loop oil supply for control of the clutch and brake is axially fixed on the housing.

![Schematic representation of hydraulic clutch / brake](image)

Figure 2.3.1.3-1: Schematic representation of hydraulic clutch / brake

- The workpiece is positioned in the die by means of walking beam systems with sensitive sequence of motions and a precision of +/- 0.1 mm.
- Upper ejectors that synchronously work with the ram movement and individual table ejectors with servo-hydraulic control, make the workpiece in function of the cycle time. Also, they place the workpiece in the correct position available for the grippers of the automatic walking beam system.
- Die spraying devices with separately programmable spraying intervals and spraying volumes keep the die temperature at a tolerable level.
- PC aided service systems are incorporated for the reduction of standstill periods in the press cycle.
- In the end, the process sequences are permanently analyzed with regard to potential improvements.

2.3.2 Tools


- In addition to other aspects, closed dies are required for the precision forging of parts without burrs. This paper shows different tool systems that allow manufacturing of straight and helical gears, connecting rods and alternator poles.
• Various concepts such as press requirements along with single and double acting tools used in closed die forging are discussed.
• Based on practical experience with spring assemblies, in order to provide the necessary closing force, an alternative closing device for forging dies is introduced that avoids the disadvantages of present solutions.


• The traditional method for forging a crown wheel is upsetting a cylinder billet followed by closed die forging to a semi finished product with a thin cylindrical plate in the center. A new technique for forging crown wheels in counter blow hammer forging has been developed.
• In the conventional method a thin cylindrical plate in the center is later sheared and scrapped. In the new proposed method, a conical tap is formed in the center allowing a thinner plate.
• A commercial software code, FORM2D, is used to optimize the tool geometry. The analysis was carried out with the conditions that the maximum force, tool pressure and totally required plastic work for the new concept must not exceed that of the existing method.
• The friction coefficient was established by comparing workpiece shapes obtained from theory and experiments. The blows were simulated in 5 incremental steps using constant velocities.

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**Figure 2.3.2.2-1: Experimental results**

• Optimization of the tool geometry is done by varying an assortment of die geometry parameters (radius, angle, etc.). Also, tools with
one central conical tap, taps in both the tools, etc. were used in the simulations.

- Full scale experiments were carried out and the following results were obtained:
  1. Productivity increased 30% as a result of reduction in number of blows from 9 to 6.
  2. Tool life increased from 1000 to 2000 pieces of crown wheels.
  3. The forging process became more stable (i.e. risk of workpieces jumping out of the die was reduced).
  4. The use of lubricants is reduced.
  5. The inclusion of taps in the center has allowed for more automation of the process.
  6. Machine maintenance is reduced.


- The use of tubular transmission shafts, especially in manual transmissions, result in weight savings in automotive drive trains. Thus, methods have been and are being developed for cost effective production of these and similar components that have an internal contour, Figure 2.3.2.3-1.

![Sample parts with internal contours](image)

**Figure 2.3.2.3-1: Sample parts with internal contours**

- Various methods and forming machine tools are used in this application: 1) Hot and warm cross rolling with mandrels, Figure 2.3.2.3-2, has been developed at the Fraunhofer Institute Chemnitz to a cost effective production method. The cycle time is between 3 to 12 seconds. 2) Radial forging (or swaging) at room
temperature, has been further developed at the University of Darmstadt, to form tubular shafts. This process, however, is relatively slow and needs several parallel operations to maintain a competitive production rate. 3) Tube hydroforming has the potential to form such parts as well. However, due to large wall thicknesses very high forming pressures are required. Thus, this application has not been practical. 4) Cold forging and extrusion is a commercial technology and uses often hydraulic presses to assure constant forming load over a relatively long press stroke.

Figure 2.3.2.3-2: Hot and warm cross rolling with mandrels

- An example part is seen in Figure 2.3.2.3-3. This part is delivered assembly ready and is manufactured by a) multiple stage warm forging, b) turning, c) boring of the 21 mm diameter, d) spline and thread rolling and e) induction hardening of the shaft and grinding of bearing seats.

- Thixoforging is the process of forming metals that have a globular and fine-grained microstructure.
- The requirement of forging parts with an easily reproducible quality leads to the necessity of optimizing die and press technologies. It is also necessary to determine, in advance, microstructures, induction heating processes, and quenching, as well as the thermal treatment that follows the forming process.
- This paper focuses on describing an optimized induction-heating unit with an integrated temperature control and also on the fundamental elements of a press used for the thixoforging process. The results of a metallographic investigation on microstructure and the effect of squeezing on the formed part are presented.
- The simulation of die cavity filling is demonstrated with these parts. The mechanical properties of parts of different thermal treatments are discussed.
- The die filling of a ‘Steering Knuckle’ is simulated and is metallographically examined. It is seen that welding of two metal fronts is possible around bars and cores when the absorption from the overflow of impurities is integrated.
- The experimental results have shown that it is possible to inductively heat raw materials for thixoforging and measure the temperature without direct contact.
- The examination of mechanical properties of thixoforged components made of AlSi7Mg and AlMgSi1 showed that depending on heat treatment, good results can be obtained. However, formation of small “dead zones” with impurities cannot be completely eliminated.
It is seen that casting alloy AlSi7Mg should be kept longer at the thixoforging temperature to create homogeneous heat penetration, while the wrought alloy AlMgSi1 should be heated a short time at the thixoforging temperature to avoid grain growth.


The use of ceramic inserts in steel forging tools offers significant technical and economic advantages over other materials. These potential benefits can however only be realized by optimal design of the tools so that the ceramic inserts are not subjected to stresses that lead to premature failure.

In this paper, data on the loading of tools is determined from a commercial forging simulation package (DEFORM HT) as the contact stress distribution on the die-workpiece interface and as temperature distributions in the die.

This data is processed as input data for a finite element die stress analysis. Process simulation and stress analysis are thus combined during the design and a data exchange program has been developed that enables optimal design of the dies taking into account the elastic deflections generated in shrink fitting the die inserts and that caused by stresses generated in the forging process.

Stress analysis of the dies is used to determine the stress conditions on ceramic insert by considering contact and interference effects under both mechanical and thermal loads.

Experimental investigations are used to verify simulation results (see Figure 2.3.2.5-1). Laboratory tests on ceramic insert dies have verified the superior performance of the Zirconia and Silicon Nitride ceramic inserts, which prolong maintenance life.

![Material flow pattern from analysis and experiments](image)

**Figure 2.3.2.5-1: Material flow pattern from analysis and experiments**

The low wear and dimensional stability of ceramic inserts results in forged products with good dimensional accuracy and eliminates the necessity for frequent refinishing. Thus, downtime is minimized and production efficiency is increased.

- New lubrication technologies in order to improve the tribological condition of the forging die and workpiece interface and thus improve die life in hot forging are discussed.
- Testing was conducted with two different dies (see Figure 2.3.2.6-1).

![Figure 2.3.2.6-1: Forging dies used in testing](image)

- Electro static powder coating technology was used to coat the forging die surface with graphite, phosphate, and lamellar boron nitride powder. The lamellar boron nitride coating showed the least amount of wear even when compared with traditional forging lubricant materials.

![Figure 2.3.2.6-2: Electro Static Powder Coating Technology](image)

- Ceramic and hard material mono-layer coated dies were also tested. The mono-layer coatings reduced wear but were susceptible to cracking and chipping.
Ceramic multi-layers applied via plasma-aided CVD coupled with a nitrated die surface offered the following advantages over a nitrated surface and/or ceramic mono-layer.
1. Energy consumption at the inner boundaries.
2. Crack deflection at phase transitions.
3. Layer support through neighboring layers.
4. Stress relaxation through stapled construction.

The layer system TiN-TiCN-TiC, with nine single layers, showed wear 20 times less than an nitrated die surface and 50% less than a TiN mono-layer coated die.

New materials for hot forging dies were also investigated. An aluminum oxide insert failed after only 150 cycles due to a poor thermal shock resistance. A silicon carbide insert also failed very quickly due to the high mechanical loads. However, both silicon nitride and SiAlON inserts demonstrated good performances in hot forging.

2.3.2.7 Kleiner, M. Klaus, A. "Manufacturer of Bent Aluminum Profiles During Hot Extrusion" (LFU - Univ. of Dortmund, Annual Report, p. 22 (ongoing research).

The objective of this study is to produce bent extruded profiles, for space frame application, by bending directly during the extrusion process. Thus, costly secondary bending operations can be eliminated and long components can be produced to desired configuration.

The process uses a conventional extrusion process. The extended profile is guided by a NC controlled bending device, Figure 2.3.2.7-1.

The process offers good contour accuracy because bending is initiated in the deformation zone within the extrusion die. Spring back is practically eliminated and there are no variations in the extruded cross section. Furthermore, residual stresses are drastically reduced.

Figure 2.3.2.7-1: Manufacture of bent aluminum profiles during extrusion

2.3.3 Process Variations
2.3.3.1 “Thixoforging of Aluminum and Copper Alloys (Research)”  
Prof. K. Siegert / IFU – Institute for Metal Forming, Technical University Stuttgart, Germany.

- Thixoforging is conducted at a temperature where the material is semi-solid. The process combines the advantages of forging (high strength and high fatigue properties) and casting (production of complex parts in a single die at reduced cost).
- Studies are being conducted on thixoforging of non-ferrous alloys, using a 500-ton hydraulic press with high slide velocity (up to 800 m/sec).
- The study aims to optimize the process and establish guidelines for process parameters such as initial workpiece temperature, microstructure of the workpiece, forging velocity, die geometry and materials.

![Figure 2.3.3.1-1: Examples of thixoforged parts](image)

Figure 2.3.3.1-1: Examples of thixoforged parts


- Semi-solid forming (SSF) or thixoforging of steel has the potential for manufacturing components from steel with complex geometries and forged-like properties at acceptable cost.
- Thixoforging of steel may be economically feasible by developing a) workpiece material with appropriate microstructure suitable for forging in semi-solid state b) tool materials such as ceramics that can withstand high temperatures.
- Research and development is being conducted in order to develop appropriate material, induction heating techniques and tool materials and design. Work is done in cooperation with industry and the University of Hannover, using a 400-ton hydraulic forging press from AP&T. This technology, if developed for practical use, would most probably utilize specially designed hydraulic presses.
Thixoforging, or semisolid forming, of aluminum components is a technology that is increasingly receiving acceptance for practical production. Thixoforged parts offer the cost advantages of die casting (use of a single die to produce complex parts) while providing increased mechanical properties in the forged component.

R&D is being conducted in a) induction heating techniques because the temperature of the semisolid billet must be very closely controlled, b) selection of the appropriate Al alloy and c) press technology. In this study a 5000kN accumulator driven high speed (up to 800 mm/sec) hydraulic press is used in the thixoforging trials. It is possible to program the ram speed versus stroke in order to determine the optimum velocity variation for successful thixoforging, and a) process simulation to predict die fill, defect formation and solidification pattern.

This study, as well as several others, applies the thixoforging technology to example parts. Experiments with thixoforged components from DIN alloys AlSi7Mg and AlMgSi1 indicate that by optimizing the process parameters it is possible to obtain mechanical properties that are nearly equal to that of forged products.
3. Materials

3.1 Steels (including stainless and high strength steels)


- Steel as sheet material offers many advantages for light construction. High strength steels (tensile strength = 1350 N/mm², yield strength = 1150 N/mm², elongation = 6%) are difficult to form and require novel forming methods as well as presses with improved characteristics, i.e. higher forming and blank holder force capacity.
- An example martensitic steel, MSW 1200, has been shown to satisfy the requirements for crash resistance as door strengthening members. After determining the tensile properties of the material a design was developed, tooling was constructed and parts were produced. This example illustrated the difficulties involved in design, tooling and equipment selection when forming high strength steels.
- Thyssen is applying the technology to the produce crash resistant chassis components, for example B-pillar support and bumper support.

Figure 3.1.1-1: Sample part formed from MSW 1200 martensitic steel


- This paper gives an overview about new and future developments in sheet metal fabrication and further processing. Special focus is given on the four process stages of sheet metal processing; metallurgy and material development, strip fabrication, semi-finished product manufacture and further processing of light weight constructions. Existing process and possible future developments in each stage are described.
- Lightweight material construction with emphasis on high strength has resulted in use of material such as high strength steels, stainless steel,
aluminum alloys, magnesium alloys and polymer materials in construction.

- The cold formability of steel decreases with increase in tensile strength. New developments are aimed at allowing better cold formability at the same strength level. Bake hardened steel, SULC-steel, IF-steel, Dual-phase and TRIP-steels are the few examples developed recently.
- Conventional aluminum alloys have low formability and high yield strength. New developments include dispersion hardening aluminum alloy sheets, which are formable and achieve a relatively high strength.
- Magnesium alloys show poor formability at room temperature. However, the formability increases in the temperature range of 200-250°C that makes suitable for forming sheet components at elevated temperatures.
- Conventionally metal strips are cast to slabs of 250 mm thickness and rolled to desired sheet thickness. Recent developments are thin slab castings of 40-100 mm thickness and are rolled in a few stages to the desired thickness, which reduces energy consumption. The next stage is thin strip casting using twin rolls as shown in Figure 3.1.2-1. The sheet is rolled to the desired thickness in one roll pass.

![Figure 3.1.2-1: Process shortening in strip fabrication](image)

- Tailored products require semi-finished products, which enable just the right amount of material to be used for the finished components that is needed to withstand the loads experienced in use.
- Important examples are sheet with varying thickness manufactured using a flexible rolling process, flow turning process and flexible tube drawing process with different tube thickness (see Figure 3.1.2-2).
- Figure 3.1.2-3 shows some innovative semi finished and finished products from sheets and tubes of varying thickness.
The following trends are of particular interest for the future of deep drawing:
1. Development of methods for components with different sheet structures. Tailored blanks through welding and/or flexible rolling.
2. Development of deep drawing process by combination of different working principles for example hydromechanical deep drawing.
3. Segmented tools and flexible blank holder with multipoint cushion table in a single action press.
5. Process simulation.

Lasers can be used for local heating to change the curvature in sheet forming (see Figure 3.1.2-4). Lasers are also used in trimming formed parts.
Another area of future research is micro forming. The role of sheet metal is not clear, however electronic industries are potential customers. The analysis of micro forming requires study of the influence of individual grains rather than multi-crystal forming and opens a whole new field of forming technology.


- Tailor welded blanks are routinely used in manufacturing body components to save weight.
- A competitive product, called tailored rolled blanks, can be produced by flexible rolling, Figure 3.1.3-1, by changing the thickness of the sheet during stiffness where it is needed. In certain instances it may be necessary to anneal the rolled material selectively to restore formability and eliminate the effects of strain hardening.
- Tailored rolled blanks have been already applied to manufacture structural automotive parts with success. These blanks offer an alternative to tailor welded blanks for producing lightweight components.
3.2 Aluminum Alloys


- Aluminum sheets are increasingly used in press operations because of its low weight and potential energy savings. The formability of aluminum is only about two third of a deep drawing steel and its low Young’s modulus results in early wrinkling and springback. This paper addresses improvements of the formability of aluminum alloys 5xxx and 6xxx series through warm forming of aluminum sheets.
- Deep drawing of rectangular pan and stretch drawing of conical rectangular pan experiments were conducted for aluminum alloys 5754-O, 6016-T4 and 1050-H14 sheet at elevated temperature to study their formability. The die, blank holder and the blank were heated to the test temperature and the punch is maintained at room temperature.
- Rectangular pan deep drawing experiments were conducted at a maximum temperature of 175°C and the aluminum alloy showed increased maximum cup height of 20-25% compared to the room temperature.
- Conical pan stretch drawing experiments showed similar results for the formability of the tested materials at high temperature.
- Hardness of the formed parts at high temperature were measured at different places and found to be close to the hardness of the formed parts at room temperature.
- The future work described by the authors is to have critical consideration of a) effect of warm forming on the product properties, b) effect of non-uniform die heating on formability of the materials and c) lubrication issues in warm forming.

- The influence of electrical discharge texture (EDT) and dry film lubrication on the forming capability of aluminum sheets is discussed.
- Dry film lubrication offers the possibility of providing both protection during material handling and lubrication during forming.
- Cup drawing tests were conducted with three EDT surfaces, two oil lubes, two dry lubes, three blank holder forces, and four blank diameters.
- The smoother surface structure showed the most forming capability. Also, the oil lubes showed better forming capability than the dry lubes. However, the dry lubes did show good formability when the blank diameter and blank holder force were optimized.
- Strip drawing tests were conducted with an oil lube, two dry lubes, two contact pressures, and two drawing speeds.
- The dry lubes showed a higher coefficient of friction than the oil lube. The coefficient of friction decreased with increasing contact pressure for both oil and dry lubes. However, the coefficient of friction decreased with increasing drawing speed for the oil lube, while it increased with increasing drawing speed for the dry lube.
- Production runs of the M3 outer bonnet of a BMW automobile were completed with an oil lube and two dry lubes.

![Figure 3.2.2-1: M3 outer bonnet die and sensors](image)

- Without optimizing the tool trim and blank holder forces, the quality of formability obtained with the oil lube could not be obtained with the dry lubes.
- This investigation showed the importance of the surface structure on the friction in forming processes and that the forming process must be optimized in order to use dry lubes.

- The forming capability of a material in stamping is characterized by its mechanical properties as well as by the tribological properties of the surface itself. The surface texture and lubricant used in the forming process mainly influence the tribological properties of the sheet. This paper describes the influence of several Electrical Discharge Textures (EDT) in combination with dry film lubes on the forming process.
- EDT surfaces in combination with dry lubes were investigated in strip drawing and cup drawing tests. Aluminum sheets coated with dry lubricants VS and ZX were tested and compared with oils ALF15 and ALG17 that are commonly used in series production at BMW.
- In the cup drawing test, 200mm diameter cups were deep drawn with sheets of three different EDT textures named A, B and C and with three different blank holder forces. Among the three textures, texture A had minimum surface roughness and closed void volume. Texture B had maximum surface roughness and closed void volume.
- Among the three textures, texture A was found to be best and texture B was worst for both dry film lubrication and with oils. Among the lubricants, ALG17 was best compared to dry lubes. Among the dry film lubricants, ZX seems to be slightly better than VS. Addition of oil to the dry lubricated sheets gave the same results with only oil applied on the sheet.
- Strip drawing tests concluded that friction coefficients for dry lubricants are higher than friction coefficients of oil ALF15. The friction coefficients of all lubricants decrease with increase in contact pressure. For change in speed, the friction coefficient of ALF15 is lower at higher speeds and friction coefficient of ZX is slightly increased at higher speeds. Dry film lubricant VS failed with the low speed. In general, ZX showed better performance than VS.
- Experiments were conducted on a sample part BMW M3 using EDT sheets with oil lubricant ALF15, dry lubricant ZX and VS. Initially press parameters were configured for EDT sheets with oil ALF15 and parts were formed without any tear and wrinkle. Sheets with dry lubricants tested caused wrinkles and consumed less energy implying a low friction coefficient contradicting the results of strip drawing test. The authors suggested that may be due to high contact pressures in practical processes compared to test conditions and the friction decreases for dry lubricants at high contact pressure.
- The experiments show the importance of EDT on the tribological system in sheet forming. Sheets with low surface roughness offer better
tribological properties. Use of dry film lubricants influence the tribological system.

- The outlook for the authors is to develop dry lubricants such that they offer low friction coefficient, less wear and are compatible with bonding sealing and painting such that the dry film need not be washed before assembly.


- Aluminum alloys are increasingly used in lightweight constructions due their high strength to weight ratio compared to steel; but the formability of Al is low compared to steel. Typically 5XXX series alloys are used for inner panels and 6XXX series alloys are used for outer panels because of the absence of stretcher marks after forming 6xxx alloys. This paper presents the research work on improving the formability of aluminum alloys by locally varying the temperature in the die. As a result 5xxx alloys of aluminum could be used to form outer panel parts and the stretcher marks in 5xxx could be eliminated in warm forming.
- Tensile test were conducted on 1.2 mm gauge sheets of aluminum alloy 5754-O and 6016-T4 at elevated temperatures.
- A5754-O alloys do not show much change in their flow behavior until 100°C, at temperatures higher than 100°C the flow stress and the work hardening coefficient decrease with temperature. The fracture strain increases with temperature especially at low strain rates.
- A6016-T4 alloy behaves differently. The flow stress and the work hardening coefficient decrease with increase in temperature. The fracture strain also decreases with increase in temperature.
- Round cup drawing experiments were conducted at elevated temperatures. The results are:
  1. The punch force decreases with increase in the temperature
  2. The limiting draw ratio increases with increase in temperature. A maximum of 2.5 was achieved for A5754-O alloy and 2.3 was achieved for A6016-T4 alloys at temperature of 250°C.
  3. The wall hardness of the formed cup is higher than the initial hardness for both alloys but it decreases with increase in the processing temperature.
- Experiments conducted on stretch drawing of conical box shaped panels concluded results similar to the round cup experiments.
- To investigate the properties of the warm formed parts, tensile test were conducted at room temperature on 10% prestrain samples at elevated temperature. The yield strength of the A5754-O and A6016-T4 alloys decreases with increase in processing temperature. However, the fracture strain increases for A5754-O alloys with increase in temperature and it is vice versa for A6016-T4 alloys.

- This paper presents the relationship between the deep drawability to the processing temperature and strain rate of aluminum alloys A5182-O and A5082-O at temperature ranges from room temperature to 250°C.
- Tensile test conducted for the aluminum alloys at the specified temperature range concluded the following.
  1. The tensile strength decreases with increase in temperature.
  2. The elongation increases with decrease in temperature.
  3. The elongation for A5182–O is higher than the A5082–O at the same temperature and strain rate.
  4. The tensile strength for A5182–O is higher than the A5082–O at the same temperature and strain rate.
- The Limiting Draw Ratio (LDR) in deep drawing is a function of both the tensile strength and the elongation. To study the temperature and strain rate influence on the deep drawability, deep drawing experiments were conducted for the aluminum alloys A5182–O and A5082–O at temperature range from room temperature to 250°C. Results of the experiments are given below.
  1. A maximum LDR of 2.6 was achieved at the temperature of 250°C.
  2. The LDR value increases as the strain rate decreases and the temperature increases for both alloys.
  3. The change in LDR is more dependent on the change in temperature than on the change in strain rate at high temperatures. This implies that an increase in temperature increases the formability and is much more effective than the decrease in strain rate.
  4. The change in LDR among the alloys was not significant at high temperatures.


- Aluminum alloys are currently used in outer body panels due their lightweight characteristics. However, the low formability of aluminum alloys, compared to steel, restricts its application in sheet forming. This paper describes an adaptive design of aluminum sheets of 6xxx series alloys for deep drawing to increase their formability.
- In the deep drawing process the material is drawn into a cavity. Fracture occurs at the punch corner when the force required to pull the material from the flange exceeds the maximum force that walls can carry. Increase in the strength of the wall or decrease in the force required to pull the material from the flange can achieve an increase in formability.
The latter task of softening the flange is achieved by laser heating the blank at the flange as shown in Figure 3.2.6-1.

**Figure 3.2.6-1: Laser irradiation strategy for round cup deep drawn blanks**

- During laser heating the temperature is raised to $400^\circ\text{C}$, at which the precipitation structure dissolves at the exposed surface. This local heat treatment causes a decrease in yield and tensile strengths at irradiated locations. The softer condition in the flange is called W-condition while the remaining part of the blank is in naturally aged T4 condition.

- Deep drawing experiments conducted on A6064-T4 blanks with laser heating at the flange zone increased the LDR from 2.1 to 2.6.

- Deep drawing experiments conducted on tailor welded Al 6064 T4 with laser heating at the flange zone increased the LDR from 2.0 to 2.36.

- To show the practical significance of adapting the material properties of the blank to the process, experiments were conducted on conventional and tailor welded blanks for an automotive door panel stamping with and without laser heating of the flange. The results of the experiments are shown below in Figure 3.2.6-2. Local laser heating in the flange region near the fracture areas allowed the material to flow easily, thereby reducing the chance of fracturing.

**Figure 3.2.6-2: Laser irradiation to improve the drawbility of a conventional blank and tailor welded blank in an automotive application**
The current work of locally optimizing blanks with laser heating has increased the formability of aluminum alloys by postponing fracture in the stamping. Future work is focused on developing new techniques to postpone wrinkling during stamping operations for aluminum alloys.


Aluminum and Magnesium alloy sheets have limited formability and are difficult to form at room temperature. However, the formability of these materials can be increased considerably if they are formed at elevated temperatures, i.e., around 200-250°C.

Forming of Sheet and Tube from Al and Mg alloys at elevated temperatures have two major advantages. At elevated temperature a) the flow stress is reduced so that lower pressures are needed for deformation and b) the formability increases, i.e. fracture is postponed. As a result, better part definition with smaller corner and fillet radii can be obtained.

Basically two alternative methods may be used to form sheet and tube at elevated temperatures. When using hydroforming with a heated liquid pressure medium mainly the material is heated and the stretch formability is increased. When using heated tooling in sheet forming it is possible to affect the flow of the blank material under the blank holder. As a result the draw depth would be increased. Research is being conducted in using both alternatives simultaneously so that the best possible process control can be achieved.


Warm forming offers the possibility to overcome intrinsic problems with the formability of aluminum, magnesium and titanium. However, there is a lack of experience in tool and process design for warm forming.

Research is being conducted to determine a) the effect of temperature on tensile properties of Al alloys 5754-0 and 6016-T4, b) the effect of temperature on drawability and c) establish how warm forming affects product properties.

The study develops information on how to design the warm forming process, how to design and heat the tools and how best to heat the blanks.

- Aluminum use in automobiles has doubled over the past decade and tripled in light trucks.
- Aluminum can a) add 6 to 8 percent fuel savings for every 10 percent weight reduction, b) save a net 20 pounds of carbon dioxide equivalents over the lifetime of the vehicle for every two pounds of steel replaced and c) allows for recycling (90% of aluminum is recovered or recycled).
- Formability of aluminum alloys with yield strengths similar to low-carbon steel is very low. Warm forming of aluminum alloys (5XXX and 6XXX series) with die and blank holder temperatures around 200-300°C increases the formability.
- Experiments conducted with rectangular conical cups from aluminum alloy 5754-O at 20°C, 100°C, 175°C and 250°C show cup heights of 35mm, 38mm, 38mm and 60 mm respectively.
- A major drawback to warm forming of aluminum alloys is the need for better lubricants. A satisfactory lubricant should possess the following qualities a) good lubrication to reduce friction, b) stability at operating temperatures (no fumes or smoke), c) nontoxic, d) good adhesion, e) ease of application, f) ease of removal and g) low cost.
- Warm forming of aluminum alloys offers the possibility of drawing complex aluminum sheet products, which cannot be manufactured at room temperature without extra forming and joining operations. Because of the complexity of various parts and lack of knowledge base, further development work is needed to establish design guidelines for warm forming.


- The paper discusses the influence of anisotropy (r-value) on hydroforming of sheet metal pairs. Experiments are conducted and compare the formability of a deep drawing steel alloy against aluminum alloy 6016-T4. Both materials exhibit similar flow stress behavior but have different levels of anisotropy.
- Hydroforming of sheet metal pairs is divided into the following process stages: a) application of blank holder force b) free forming of a bulge c) contact between the die and the bulge d) forming into die radii e) flange clamping and f) calibration. The second stage, which is free forming of a bulge, is similar to a deep drawing operation.
- Experimental results show that the aluminum alloy, which has an r-value of 0.6, experiences less draw-in compared to the steel alloy with r-value 0.206.
of 1.8. Consequently, form filling of the die is poor for the aluminum alloy.

- In hydroforming, deep drawing of the flange does not start until the material has strain hardened sufficiently by formation of a spherical bulge due to stretching. Materials with smaller values of anisotropy require more time to reach this critical flow stress; therefore, they tend to demonstrate more stretch forming and less draw-in.
- Results show that a greater r-value is required to produce more draw-in during free forming of a bulge. Aluminum alloys with low r-values cannot use this stage efficiently and therefore exhibit poor form filling.
- The author recommends the following four solutions to alleviate this problem: a) use aluminum alloys with higher r-values b) apply local heat treatment to the flange just prior to forming c) hydroform the aluminum alloy at elevated temperatures using a warm fluid and d) reduce the flow stress in the flange by using a heated tool.

3.3 Magnesium Alloys and others


- Magnesium sheet has been used in automotive applications only in a few selected cases, although magnesium die-casting is used extensively. The trend to increase strength to weight ratios opens new possibilities for using magnesium in automotive applications. However, magnesium sheet is difficult to form at room temperature while its formability around 200-250 °C is quite good.
- The “Salzpitter Mg Technology A.6” is working with the University of Hannover to develop forming methods and tooling to expand the application of magnesium sheet.
- Heated tooling (up to 250 °C) has been developed and many parts have been formed. The use of hydroforming of heated magnesium sheet is also being developed along with methods for assembling the sheet using mechanical clinching techniques. Example parts (door inner and seat structure) as well as tailor welded magnesium blanks have been formed in cooperation with VW.

- This paper outlines the actual and possible use of magnesium alloys in automobiles and aims to tackle questions such as a) how might the use of Mg in automobiles develop? b) what are the basic requirements? and c) what R&D efforts are required? with the aid of an example component and projects.
- The analysis presents details for each of the four vehicle modules namely drive train, interior, body, and chassis, the magnesium components already in use or theoretically capable of introduction, differentiated according to the time frame required for introduction and the likelihood of realization.
- In the drive train units, magnesium alloy castings are being used. The existing alloy AZ91-hp shows greater tendency towards creep; hence a new alloy has been developed to have creep rate one tenth of the existing alloy. However, feasibility for mass production of components from the new alloy needs to be investigated.
- In the interiors, use of magnesium alloys is restricted, as the magnesium alloy castings do not meet safety requirements. Optimized casting methods and lightweight design expertise would help to find application of magnesium alloy in safety related parts such as seats.
- The chassis area offers the greatest challenge in using magnesium alloys due to its demanding safety requirements. New casting methods, optimized wrought alloys and forged components could offer the prospect of improvements in this area.
- In the body, hybrid panels with exterior aluminum sheet and interior magnesium thin walled die castings are presently used. Formed magnesium sheets for body would significantly reduce weight. Current research activities are focused on developing forming technology for
processing magnesium sheet and development of corrosion resistance strategies for magnesium.


- Magnesium alloys have the lowest density among all metals and are used as die-castings in different products. Formed magnesium sheet parts can find increased application in products such as automobiles and can significantly reduce weight and save fuel consumption. However, the magnesium alloys show limited formability at room temperature. This paper addresses the formability characteristics of magnesium alloy sheets at high temperature and the feasibility of warm sheet forming processes in practice.
- Magnesium alloys sheets (AZ31B) tested showed increased formability at elevated temperature of 200-250°C. The Limiting Draw Ratio (LDR) was increased to 2.7 at 235 °C from 1.4 at room temperature.
- Magnesium alloys show high rate sensitivity at warm forming hence forming speed is an important factor in warm forming of magnesium alloys.
- An example industrial part has been formed using magnesium alloy sheet (AZ31B) at elevated temperature to show its practical feasibility.
- Concepts for designing warm forming tooling and two methods for heating the blank are discussed.


- Today magnesium alloys are one of the lightest metallic materials that can be used in automotive applications. Currently magnesium parts are processed by die casting and are limited to engine components such as housing. A promising alternative can be seen in construction parts that are manufactured by forming processes. This paper presents the work done on forming magnesium alloy sheet and billets using sheet forming and forging processes respectively.
- Magnesium alloys show limited formability at room temperature and cannot be processed by conventional forming processes at room temperature. Magnesium sheet specimens (AZ31 alloy) tested using tensile test revealed that the stress and strain hardening decreases with increase in temperature. The fracture strain increases with increase in temperature. The temperature range of 200-300°C was found to be the optimum processing range.
- Upsetting tests on magnesium billets were conducted at 300°C. The flow stress decreases at higher stains due to an increase in temperature
of around 70°C during testing. The flow stress at high temperature was sensitive to strain rate.

- To determine the formability of magnesium alloy sheet, deep drawing and stretch forming tests were conducted on magnesium alloys AZ31B, AZ61B and MN150. The alloy AZ31B has the maximum formability in stretch forming and deep drawing tests. A maximum LDR of 2.5 was observed for AZ31B Mg alloy at a temperature of 225°C.
- Deep drawing experiments with complicated tooling further confirmed that deep drawing of magnesium parts for industrial applications is possible.
- Success in application of magnesium in forging depends on the ability to precision forge magnesium alloys. Know-how for precision forging is not well established, therefore, a fundamental investigation on magnesium alloy forging is presented here. FE simulations were performed using the upsetting test data to design a precision forging process for a sample sprocket made from magnesium alloy AZ31. Optimized billet temperature was between 300-380°C while die temperature was 250°C. Graphite was used as a lubricant for precision forging of a sprocket from magnesium alloy.
- Forming of sample parts from magnesium alloys indicate that formed magnesium alloys are future alternative materials for lightweight constructions. Future research work will focus on developing forming processes for manufacturing complex parts from magnesium alloy sheets and billets.


- Magnesium alloys due to its low density offers an alternative for future lightweight constructions. Magnesium alloys are currently processed through die-casting and hot extrusions. Cold forming of magnesium remains a great challenge today due to its low formability at room temperature. This paper presents research done on improving the cold formability of magnesium alloys and the possibilities of improving the mechanical properties.
- Simple upsetting of magnesium alloys gives a maximum reduction of just 7 % and cracks appear along the maximum shear plane.
- Authors used a conical ring and a conical casing (Figure 3.3.5-1) such that the radial pressure creates a hydrostatic stress state before the material begins to flow in upsetting. The experiments showed an increased formability for magnesium alloys.
Cold forward extrusions experiments were conducted on magnesium billet that has a hydrostatic stress state induced due to aluminum alloy casing around it (Figure 3.3.5-2). The experiment result shows that the magnesium alloys can be cold formed with hydrostatic stress induced and improvement in their mechanical properties are significant.

Combination of upsetting and backward extrusion experiments was conducted on the magnesium billet and aluminum alloy casing as shown in Figure 3.3.5-3. During the experiment the magnesium billet was upset in a hydrostatic stress state due to the radial stresses caused by the backward extrusion of aluminum casing. The magnesium alloys showed improved cold formability.

The experiments showed that cold formability of magnesium alloy can be improved by inducing hydrostatic stress state during the processing.
stage and this can be exploited in industry for cold forming of magnesium alloys.

Figure 3.3.5-3: Experimental setup for combined upsetting and backward extrusion


- Magnesium alloys are commonly used in automotive applications for die casting components due to their high strength to weight ratio. Application of magnesium alloys in sheet metal parts is restricted due to its low formability at room temperature. However, magnesium alloys show increased formability at temperatures around 225°C. This paper presents methods to improve the formability of magnesium alloys by locally varying the temperature in the tool.
- Tensile tests conducted on magnesium alloy AZ31B indicated that the flow stress and strain hardening coefficient decreases with increase in temperature. The fracture strain increases as the temperature increases.
- Deep drawing tests were conducted using a tooling with heating capabilities. The die and the blank holder were maintained at the same temperature using electric heaters. The blank is heated when it is clamped between the die and blank holder. Tests were conducted at two different temperatures for five new alloys. A maximum LDR of 3.0 was achieved for a new alloy. This concluded that LDR is strongly dependent on the processing temperature and the alloy composition. The composition for the new alloys was not specified.
- Experiments were conducted for forming a rectangular pan using magnesium alloy AZ31B with homogeneous die temperature. A maximum depth of 75 mm was achieved at uniform die temperature of 225°C. In the rectangular pan drawing the corners are subjected to radial stretching and tangential upsetting whereas the straight sections
are subjected only to radial stretching. Due to the non-uniform stress state in the flange, a differential heating with high temperature in high strain zone allows uniform material flow and increases the draw depth.

- The partial tool heating setup used in partial heating experiments is shown in Figure 3.3.6-1. A temperature of 150°C was maintained in the straight walls (Circuit B) and 225°C in the corner walls (Circuit A). A pan height of 98 mm was obtained in the experiments without tearing and wrinkling for partial die heating. This shows a remarkable improvement in formability.

![Figure 3.3.6-1: Tool setup for partial die heating in warm forming of magnesium alloy](image)

- Partial die heating could not only increase the formability of magnesium alloys but also reduces the amount of heating required for the process and the process time.
- Warm forming of magnesium parts opens an interesting method for the production of large-area and very thin-walled components like body shell panels. The acceptance of magnesium sheet in automotive applications depends on the availability of competitive manufacturing and processing systems for the entire production chain from the intermediate material to the finished product. In this context the future work will focus on the development of joining systems and anti-corrosion concepts.


- Magnesium alloys with high strength to weight ratio offer a potential alternative material for lightweight constructions. Increasing application of magnesium alloys in structural components could be realized by processing the magnesium through forming operations such as sheet metal forming and bulk forming. Magnesium alloys show low formability at low temperature and the formability increases at elevated temperature. To realize economical magnesium products with high dimensional accuracies using forging, precision forging without secondary operations is desirable. This paper presents the research done in establishing optimum processing temperature ranges for
precision forging of magnesium alloy ZK60 using the upset test and backward extrusion test.

- Upsetting tests were conducted at temperature range of 100-400°C. The upper limit of 400°C was set as magnesium alloys undergo rapid oxidation at temperatures above 400°C. At temperature ranges of 100-200°C the billets fractured for small reductions in height. At temperature ranges of 200-250°C the specimens deformed non-symmetrically as shown in Figure 3.3.7-1. The billets could be compressed to 30-50% of their original height. Barrel shaped billets were obtained in the temperature range of 300-400°C. From the experiments, a temperature range around 300°C was found most suitable for precision forging. The flow stress curve shows strain softening characteristics at high temperature and the flow stress decreases as the temperature increases.

- Backward cup experiments conducted at 300°C further confirmed the temperature range for processing magnesium alloys. Cups of sidewall thickness 0.6 mm and bottom wall thickness of 1.0 mm could be achieved as shown in Figure 3.3.7-2. At temperatures lower than 250°C cracks were observed on the inside and outside wall surfaces.

- FE simulations of upsetting and backward extrusion tests were conducted to predict the fracture criteria for magnesium alloys. The failure criterion of maximum tensile stress gives good agreement with experimental results.

![Figure 3.3.7-1: Results of upsetting test on magnesium alloy ZK60](image)
Figure 3.3.7-2: Results of backward cup extrusion test on magnesium alloy ZK60 at 300°C
4. Software

4.1 Sheet Forming

4.1.1 “Simulation of the Dynamic Behavior of Transfer Presses (Research)” Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

- Usually in transfer presses the second die station is devoted to blanking. In this operation the press force increases very rapidly and then it is released when the operation is completed. The sudden force release causes vibrations that may affect the guiding of the tooling and the tolerances in production parts.
- The dynamic behavior of the press and its influence on part quality are investigated.
- The press structure and the slide are modeled via FEM. The guides and bearing surfaces are represented as non-linear spring/damping elements. The press vibrations, caused by the force-displacement curve of the blanking operation, are simulated and compared with experimental data.

![FEM modeling of press vibration during blanking](image)

**Figure 4.1.1-1: FEM modeling of press vibration during blanking**


- The paper discusses the current state of numerical simulations in sheet metal forming industry and possible future developments.
- Macropscopic instabilities leading to necking and wrinkling complicate the numerical treatment of sheet metal forming. Springback and residual stresses, due to elastic unloading, in the workpiece material are critical issues. These and other complications lead to the later start of the industrial application of sheet metal forming simulation.
The current industrial goals for forming simulations can be summarized as follows: a) time reduction, b) cost reduction, and c) increase in product quality.

The following simulation results are desired: a) strain and thickness distribution, b) time tracing of important material zones, c) failure indicators for wrinkling, fracture, loose metal, rabbit ears, etc., d) post-failure data such as number and amplitude of wrinkles, e) optimum blank shape, f) location and position of draw beads, f) springback values, g) residual stress distributions, h) blank holder pressure, and i) punch loads.

The first state of the deep drawing of a wheel cover is shown in Figure 4.1.2-1. The figure shows the thickness distribution at the end of the drawing stage. Development of wrinkles in the free zones can be seen.

Figure 4.1.2-1: Simulation of a wheel cover

Expected future developments in finite element simulation of sheet metal forming operations are as follows: a) increasing analysis accuracy, b) increasing analysis capabilities, c) new visualization techniques, and d) optimization abilities.

The development and application of new constitutive equations, failure criteria, and friction models is expected to increase simulation accuracy. Better material models are required especially for high-strength steel and aluminum alloys. Springback and residual stress computations must also be improved.
• The desire for increasing analysis capabilities such as incorporation of elastic die and press deflections into the sheet forming simulation requires an increase in existing code speed.
• Due to extensive amounts of post-processing data and increasing complexity of problems, new virtual reality visualization techniques are required.
• Optimization of blank geometry and blank holder pressure requires implementation of optimization algorithms in the FEM code. This will allow sensitivity analysis for many parameters and eliminate further trial-and-error procedures.


• A new method for determining the stiffness of machine tools is discussed. Results of the new method are compared to current techniques. A vertical machining center, which is shown in Figure 4.1.3-1, is studied. The machining center consists primarily of five modules a) headstock, b) column, c) table, d) saddle and e) bed unit.

![Figure 4.1.3-1: Vertical machining center consisting of five modules](image)

- The current technique, which is called Single Module Method (SMM), has the advantage of a smaller finite element model. With this technique, single modules from the machining center are modeled separately. It is necessary to transform loads applied on the cutting tool as well as those on the workpiece into equivalent forces on each module. The boundary conditions for each module are also unique and difficult to determine. With this method, it is not possible to know the influence of the stiffness of individual modules on the entire strength of the machine tool.
- The proposed technique, known as Hybrid Modeling Method (HMM), uses a detailed FEM mesh on one of the modules and coarse meshes
on all other modules. External loading only needs to be applied to the cutting tool and workpiece. A cumbersome procedure to transform the external loads into equivalent forces as required by SMM is avoided. The true elastic modulus is applied to the fine meshed member while the elastic modulus for the other four members is set fictitiously high. Therefore, the coarse meshed members are treated as rigid bodies and the fine meshed member elastically deforms. This allows computation of the stiffness for the fine meshed member.

- Figure 4.1.3-2 shows hybrid models of the machining center used in the HMM analysis.

![Figure 4.1.3-2: FEM models showing fine column and table mesh](image)

- Results of the FEM analysis for SMM and HMM show that SMM predicts a smaller stiffness for the headstock, saddle and table. However, SMM predicts a higher stiffness for the column and bed.
- The SMM results are more questionable because the load and boundary conditions may be inaccurate. However, the load and boundary conditions for the HMM models are accurate.
- The HMM technique allows for comparison of individual member stiffness. Thus, the weaker member can be identified and strengthened. HMM provides the contribution of individual members to the overall stiffness of the machine.


- The metal forming industry is increasingly utilizing practical and proven CAD, CAM and CAE techniques, including process simulation, for rapid and cost effective process design and die manufacture. Simulation of metal forming is applied to eliminate defects, optimize process variables and to predict die stresses for preventing premature die failure.
- This paper summarizes the state of the simulation technology and reviews various applications in forging, stamping and tube hydroforming.
that have been implemented at the Engineering Research Center for Net Shape Manufacturing (ERC/NSM). In addition, a brief discussion is given on how simulation techniques, successfully used in manufacturing can also be applied to some machining operations.

- From the literature review and communication with the industry, it is found that, in forging, 2D process simulation is well accepted by researchers and the industry. As the computer speeds increase and improved algorithms are developed, the simulations of very complex 3D geometries are becoming practical.

- Some of the applications in which FEA is used at the ERC in massive forming are Die and Process Sequence design in cold forging, Prediction of fracture in cold forged parts, stress analysis for tool life improvement. Recently ERC/NSM developed a methodology to calculate forces and quality of cropped bars through two dimensional process simulations under plain strain conditions.

- In stamping, one step codes have given the product designers a tool to validate their work and incremental codes are allowing process engineers to optimize die and production designs.

- In stamping, an optimal blank geometry was predicted for a cover of an excavator cabin from Komatsu Ltd, Japan using FAST_FORM3D and was compared to the experimentally developed blank shape. The experimental and the blank shape predicted by simulations are similar except for some minor differences.

- Simulations were also carried out for the sheet and tube hydroforming. Comparison of predicted and measured thinning distributions indicated that the process predictions were close to experimental values. This close agreement verifies that simulation is a good tool to analyze hydroforming.

- Sheet forming codes are improved rapidly and in the future we can expect that these codes will automatically optimize the stamping process and predict optimal variations in the blank holder force.

- Machining operations also offer a fertile area of applications of FEA simulations. In the next few years we can expect FEA to assist tool insert design and optimize process conditions.

### 4.2 Tube Hydroforming


- The paper presents simulation results on prebending and hydroforming processes that are used to form an automotive tie bar, which is placed at the front of the passenger compartment and supports the instrument panel and steering wheel. The shape of the tie bar as well as several cross-sections along the tie bar are shown in Figure 4.2.1-1.
Prebending simulations with a rotary draw bending machine and a bend die are carried out to obtain the shape change of cross-sections and thinning of the tube. The rotary draw bending machine tool set used for the FEM simulations is shown in Figure 4.2.1-2 below.

FEM simulations of the bending process are also used to account for springback in the bent part.

The thickness distribution in the tube after bending is shown below in Figure 4.2.1-3. The figure shows that the minimum thickness is 1.7 mm while the maximum thickness is 2.4 mm (initial tube thickness is 2.0 mm).
The hydroforming simulation model is composed of the prebent tube and a split die for forming the required tie bar geometry. The dies and prebent tube geometry are shown below in Figure 4.2.1-4.

The predicted wall thickness distribution for the final part, after hydroforming, is shown in Figure 4.2.1-5.
Experimental results are used to validate the FEM simulations. The results show that FEM simulation can be used to optimize bending and hydroforming of an automotive component.


An adaptive FEM technique capable of detecting defects in a tube hydroforming simulation and promptly correct the loading path, i.e. internal pressure vs. time and axial feed vs. time, is discussed. These loading paths are largely responsible for the success of any tube hydroforming operation.

Because simulating various loading paths on a trial and error basis is time consuming, either an optimization strategy utilizing an AI software package to optimize process parameters or an adaptive simulation approach capable of detecting the onset of defects and correcting the loading path should be employed.

The ERC/NSM has developed an adaptive FEM methodology.
Because increasing the internal pressure or decreasing the axial feed rate can remove wrinkles in tube hydroforming, they can be allowed to grow to a certain dimension. Then, they can be detected geometrically and the appropriate loading path correction can be made.

The ERC/NSM developed a new geometrical wrinkle indicator based on the surface area to volume ratio of the tube with the following advantages:
1. Computationally inexpensive.
2. Suitable for many part geometries.
3. Sensitive to small and large frequency wrinkles.
4. Independent of the mathematical formulation of the FEM code.

The new geometrical wrinkle indicator was evaluated in an unwrinkled hydroforming process, a slightly wrinkled process, and a severely wrinkled process. Processes were selected which illustrated good agreement between FEM and experimental results. By plotting the wrinkle indicator for all three processes, a critical wrinkle indicator was determined.


Research and development activities at the ERC/NSM relating to the quality of tube material, lubrication and friction in tube hydroforming, and process simulation with FEM are discussed.

In order to obtain successful FEA results in tube hydroforming processes, accurate tube properties must be available. Because the sheet materials are further strained in the roll forming operation, using the properties of the sheet for the tube may lead to inaccuracies.

The ERC/NSM has employed a bulge test in order to determine the flow stress, anisotropy, and forming limit diagram of the tube.
Using a suitable lubrication in a tube hydroforming process can help avoid premature defects such as wrinkling and bursting.

Three friction zones exist in a tube hydroforming process.

The ERC/NSM has developed or employed tooling to simulate each of these friction zones such that lubricants for tube hydroforming processes can be evaluated.

The ERC/NSM has developed guiding zone tooling similar to that from the University of Darmstadt-Germany. By measuring the friction force and the internal pressure, Coulomb’s law can be used to determine the coefficient of friction.
The ERC/NSM has employed the limiting dome height test in order to evaluate friction in the transition zone. The principle is that a low coefficient of friction should cause maximum thinning near the apex while a high coefficient of friction should cause maximum thinning away from the apex.

The ERC/NSM has also developed tooling for evaluating friction in the expansion zone. FEA was used to determine that a pear shaped tooling shows the most sensitivity to friction variations. The lubricants are evaluated in terms of wall thickness distribution, protrusion height, and bursting pressure of the tube.
Because the success of a tube hydroforming process depends on the loading paths, i.e. internal pressure vs. time and axial feed vs. time, the ERC/NSM has worked to develop an FEM approach that is more efficient than simple trial and error to determine the appropriate loading paths. A self-feeding approach and an adaptive simulation approach have been employed.

The self-feeding approach is a baseline approach used to determine the time and amount of tube material that will flow from the guiding zone to the expansion zone when no axial feed is applied and no friction exists. A scale factor is then employed in order to account for friction.

The adaptive simulation approach is based on the ability to detect a defect such as wrinkling or necking and then employing the appropriate corrective actions to the loading paths (figure shown above). A geometrical wrinkling indicator based on the ratio of the surface area to the volume of the tube was developed.

The wrinkling indicator was evaluated for hydroforming processes that demonstrated no wrinkling, slight wrinkling, and severe wrinkling. In all three cases, the wrinkling behavior predicted by FEM and experiments were in close agreement.

Therefore, results showed that the wrinkling indicator was:
1. Easy to implement and computationally inexpensive.
2. Suitable for a wide range of die geometries.
3. Able to detect inward wrinkles and technologically significant outward wrinkles.


Virtual manufacturing of tube hydroforming parts and cost effective finite element simulation approaches were the topic of this presentation.
• The hydraulic bulge test and the pear shape expansion test provide accurate flow stress and friction data, respectively, for finite element simulation.

• Traditionally, the loading paths for tube hydroforming, i.e. internal pressure vs. time and axial feed vs. time, were determined by a trial and error approach to finite element approach.

• The ERC/NSM has developed an adaptive simulation approach in which the onset of defects such as wrinkles are detected and then appropriate corrective actions to the loading paths are employed (figure shown above).

• The wrinkle indicator was based the ratio of the tube surface area to the fluid cell volume.

• The ERC/NSM has also developed an optimization simulation approach to blank holder force control in the drawing of a conical cup.

• This approach employed an objective function and two constraint functions. The objective function to be minimized was a function related to the maximum thinning. The constraint functions limited flange wrinkling and side-wall wrinkling to a certain critical value.

\[ \text{Figure 4.2.4-1: ERC/NSM blank holder force optimization methodology} \]

4.3 Rod and Billet Forging


• This paper discusses the benefits of FEM simulations in forging die design with emphasis on detection of material defects and die optimization.
Recent development in forging simulation software has focused on a) extending the software capabilities for the simulation of more complicated problems, b) improvements in software interface and affordability and c) developing methods for the most effective implementation of simulation software in the industrial environment.

The main requirements for cost effective simulation are a) the software must be understandable to shop-floor engineers and die designers, b) the software must be available for many people in the company and c) the software must provide automatic simulation of many variants of a forging job in a short time.

FEM simulation can provide accurate prediction of material flow in a metal forming process and allows for analysis of die filling, detection of forming defects and grain flow analysis.

![Figure 4.3.1-1: Flow-through defect occurring at end of stroke](image)

Simulation can be used to determine the optimal preform shape that provides uniform and concurrent filling of the die cavity while minimizing process load and tooling wear. Traditional trial-and-error techniques, which are very inefficient, are the alternative to numerical simulation.

Benefits obtained from forging simulations are a) ensured filling of the die without defects, b) improved material usage, c) reduction in process
load and d) increase in tool life due to smaller forces and optimized material flow.

- FEM simulation can also be used to analyze die stresses and deflections. Equivalent stress distributions can provide insight into possible trouble areas in the tooling, prior to development. Proper corrective actions can be taken to modify or redesign the tooling to minimize the stresses. Tool deflections can be investigated and reduced prior to production.

![Figure 4.3.1-2: Elastic deflection of upper and lower dies (magnified)](image)

- FEM simulation can be used in the die design stage to a) increase tool life through optimization of the die assembly and b) development of profiled die shapes that compensate for elastic deflection.
- FEM simulation can provide the following quality improvements a) achievement of accurate geometry with tight tolerances, b) controlled grain flow and macrostructure, c) determination of process windows, d) prediction of fracture in formed parts.
- Accurate job quotes can be obtained from preliminary simulations thereby reducing risk and increasing profit margin. Animations from simulations provide great presentation tools to sales personnel. Process and die design engineers can design a robust process with increased tool life.

4.3.2 Doeringer, M (2000) "The Application of DEFORM in Metal Forming", technical paper provided by Schuler, Inc.

- Commercial software packages based on Finite Element Method (FEM) are used routinely for metal flow simulation and die development.
- The software to capable to predict potential defects so that die and perform designs can be improved to avoid folds and cracks. An example given for shaft shoulder forming in Figure 4.3.2-1.
Figure 4.3.2-1: Simulation of shaft shoulder forming in DEFORM

4.3.3 “Development of a Software Module for the Determination of Tool Life in Cold Forging (Research)” Prof. M. Geiger – Institute for
The application of the finite element method offers considerable opportunities in the development of highly loaded tool systems for bulk metal forming processes.

The prediction of tool life and probable failure cause has gained significantly in importance.

Cold forging tools from industry are analyzed by calculating the process dependent load and by evaluation of real tool life data and its statistical characteristics.

The calculated tool load and the tool life data form a knowledge base for a software module, which can be used for tool life prediction.

Correlation between tool load and the expected tool life is performed by the application of an artificial neural network.


The manufacturing industry is increasingly utilizing practical and proven CAD, CAM and CAE techniques for rapid and cost effective process design and die manufacture.

Process modeling is used in massive forming to predict material flow, stress and temperature distributions, stresses and forces exerted on the tools and to predict potential sources of defects and failures.

Simulation of 2D problems e.g., axisymmetric and plane or near plane strain is truly state of the art. However 3D simulations is still not widely used in industrial practice because it is not always cost effective and requires considerable engineering and computational time.

Several issues as material properties, geometry representation, computation time and remeshing capability must be considered in cost effective and reliable application of process modeling.

Advanced process simulation tools are now capable of studying residual stress after heat treatment, including both micro structural effects as well as thermo mechanical influences and modeling of quenching process for cracking and distortion.

The numerical simulation of forging processes with a finite element method based code assists the forging engineer in establishing and optimizing process variables and die design.

Current developments are being reported on the simulation of ductile fracture. Developments are also reported in the fields of machining, welding and a wide range of topics related to phase transformation and specialized heating methods.

As computer speeds increase and improved algorithms are developed, the simulation of very complex 3D components is becoming possible.
In the near future, coupled large deformation processes including microstructure analysis will be practical. In due time it should be possible to analyze the entire manufacturing process. This will allow designers to include residual stresses and grain flow in their product design and application analysis.
5. Other Supporting Technologies

5.1 Tool Coatings


- A new device, which uses a bending test, for evaluation of the anti-galling performance of tools is developed and the forming of aluminum sheets is studied.
- The testing apparatus allows easy exchange of inexpensive cylindrical tools, which can be replaced and repolished easily.
- Tools tested are as follows:
  1. Cemented carbide
  2. SDK11
  3. Conductive ceramics consisting of ZrO₂ and NbC
  4. Cermets consisting of MoB and Ni
  5. Coated tools with SDK11 substrate
     - TiC (CVD)
     - TiN (PVD)
     - CrN (PVD)
- White spindle oil with chlorinated paraffin is used as the lubricant (Cl content of 0, 5, 10 and 20 wt%) and is applied to the sheet surface by brushing.
- An anti-galling index is defined from the wall area of the bent specimen, galling area, initial surface roughness of sheet and surface roughness of galling surface.
- MoB-base cermets show the best anti-galling performance followed by cemented carbide.
- TiC, TiN and CrN coated tools show similar anti-galling performance and are not as good as MoB-base cermets and cemented carbide.
- Coated tools out perform the uncoated SKD11 tool.


- A bending test is used to evaluate the anti-galling performance of a diamond-like carbon (DLC) coated tool, with a hardened high-speed tool substrate, for aluminum. Figure 5.1.2-1 shows a schematic of the bending test.
Results from the DLC coated tool are compared against results from MoB-base cermet and cemented carbide coatings, which provided excellent anti-galling performance in previous work performed by the authors.

Three lubrication conditions are employed during experiments:
1. White spindle oil with chlorinated paraffin (Cl content 5 wt%)
2. White spindle oil without chlorinated paraffin (environmentally friendly)
3. No lubricant – DLC coated tool only

An anti-galling index is defined to allow relative comparison between the three coatings.

A schematic view of a bent specimen is shown in Figure 5.1.2-2 below.

All coatings provide acceptable results when white spindle oil with chlorinated paraffin is used as the lubricant. However, the DLC coated tool provides the lowest surface roughness.

Only the DLC coated tool provides acceptable results when the lubricant is white spindle oil without chlorinated paraffin. The anti-galling index increases rapidly after several forming operations for the MoB-base cermet and cemented carbide coatings, causing severe galling.

The bending test can be performed with the DLC coated tool and no lubricant; but, the surface roughness of the sheet and anti-galling index increase. However, it is interesting to note that the anti-galling index
obtained for the DLC coated tool with no lubricant is almost the same as the anti-galling index obtained for the cemented carbide coated tool with white spindle oil containing chlorinated paraffin.

- DLC coated tool has excellent anti-galling performance for aluminum.


- Physical vapor deposited (PVD) coatings, which are widely used to increase tool life, are typically applied to heat-treated, ground and polished tool steels (i.e. high-speed steels).
- Deposition of a 2.5 μm titanium-nitride (TiN) coating onto an inexpensive low alloy cast steel with rough surface finish, 3 μm, and low hardness is investigated.
- Friction and wear behavior is simulated using a strip drawing test at two sliding speeds (100 mm/s and 50 mm/s) with oil at 40°C applied as the lubricant. Normal force, friction force and sheet speed, before and after rolls, are recorded while coefficient of friction (C.O.F.) and sliding speed are calculated.
- Three materials are tested on the strip drawing apparatus
  1. Low-carbon steel
  2. Zinc plated low-carbon steel
  3. Aluminum alloy AA6110
- Results show that the C.O.F. is reduced with the TiN coated tool for all materials and contact normal force can be increased in most cases.
- A cost effective increase in tool life and reduction in C.O.F. can be realized with TiN PVD coatings on soft substrates.
- Soft substrates are susceptible to deformation due to high friction forces. Combined with the high surface roughness of the substrate, these friction forces can cause high stress states inside the coating, which can lead to catastrophic failure of the tool.
- The advantages of ease in workability of the inexpensive soft substrate do not outweigh the possibility of catastrophic tool failure.


- DUPLEX treatment is a combined process consisting of substrate surface modification by plasma nitriding and subsequent physical vapor deposited (PVD) coating.
- Substrate surface and subsurface hardening up to a few hundred micrometers, prior to PVD coating, is an advantage of DUPLEX treatment.
- Plasma nitriding with a large diffusion depth provides a stable base for subsequent PVD coating, which should be between 5-10 μm thick.
- Experiments are performed with AISI H11 forging dies, which are low pressure pulsed plasma nitrided prior to PVD multilayer coating with BALINIT® FUTURA-TiN/TiAlN, 4.0 μm average coating thickness. The dies produce a holder for an automobile shaft from AISI 1045 steel in two press strokes. Figure 5.1.4-1 shows the production part.

![Production part](image)

**Figure 5.1.4-1: Production part used for testing**

- DUPLEX treated dies and die inserts are compared to dies and inserts that are gas nitrided.
- Gas nitrided dies perform better for the first stroke of the process. However, DUPLEX treated dies for the second stroke (trimming flash and calibration) and DUPLEX treated inserts (used to forge openings in shaft) out performed their gas nitrided counterparts.
- DUPLEX treatment parameters, such as plasma nitriding depth and PVD coating thickness, need to be further optimized in order for DUPLEX treated dies to out perform gas nitrided dies for the first stroke.


a. Pressure die casting of aluminum alloys
   - DUPLEX treatment was used on pressure die casting tooling (plasma nitriding followed by PVD coating with CrN).
   - Service life of the dies increased in production by 200-300%.
   - A 15-40% savings in cost per injection was realized due to a decrease in tooling maintenance, less machine downtime and less set up time.

b. CrN coating on aluminum hot extrusion dies
Hot worked steel disc die, with 80 mm opening, was made from AISI H13 material and coated with a 3 \( \mu \)m thick CrN layer.

The traditional extrusion procedure required the die to be cleaned with SiC abrasive paper every seven billets, cleaned with NaOH solution after every 100 billets and discarded after approximately 400 billets (billet dimensions of 280 mm diameter and 550 mm length).

The coated die is sprayed with a water solution of NaCl lubricant every 10 billets. More than 250 billets are extruded without cleaning and without loss of dimensional accuracy.

Use of a coated die increased the throughput of extruded aluminum, gave up to a 300% increase in die life, provided the final part with improved surface finish and reduced the operating cost.

c. Hot forging of steel parts

- See section 5.1.4.


- The influence of DUPLEX treated composites on tool durability for hot plastic working is studied.
- DUPLEX treatment method was used to prepare the tools (regulated gas nitriding to 80 \( \mu \)m depth followed by PVD coating).
- Four PVD coating materials were tested
  1. TiN – 3.0 \( \mu \)m thickness
  2. CrN – 4.3 \( \mu \)m thickness
  3. (Ti,Cr)N – 3.8 \( \mu \)m thickness
  4. Ti(C,N) – 2.8 \( \mu \)m thickness
- Forging dies, made of ISO Steel 35CrMoV5 and designed for the plastic working of automotive half-shafts, were tested by tracking required maintenance.
- Results show that the TiN coating increased service life by 1.1% compared to a tool that was nitrided but not coated; while CrN, (Ti,Cr)N, and Ti(C,N) increased service life by 89%, 33% and 11% respectively (see Figure 5.1.6-1 below).
Results show that TiN and CrN have a similar resistance to mechanical loading but CrN has a significantly larger resistance to thermal shock.


- The influence of excimer laser treatment of a TiN coated tool surface on tribological behavior in cold forging is investigated.
- Excimer lasers, particularly suited for surface treatments due to high precision in texture depth, are high-pressure gas lasers that emit pulsed radiation in the UV range of the electromagnetic spectrum.
- Micro textures can be produced in almost any material (metals, glasses, ceramics and polymers) using laser excimer radiation.
- Tool life tests are completed on a system used for the production of rivets. A 5.2 mm diameter punch, 2 μm thick TiN PVD coating on a high-speed steel substrate, is used to perform a backward cup extrusion to produce the rivet.
- Texture depth should be less than 1 μm and texture size should be less than a few 100 μm in the lateral direction to prevent an increase in friction.
- Micro texturing increases the service life of the tool by approximately 75% if the textures are designed correctly.
- Micro textures act as pockets that supply lubricant and remove wear particles during the metal forming process, thereby increasing tool life.


- The effect of oxide and carbon based coatings are evaluated in dry blanking of 1 mm sheet steel (Rfe80) and brass alloy (CuZn37).
1. Dry blanking of 1 mm thick Rfe80 steel
   - TiN+WOx, a specially developed oxide based coating for dry blanking of Rfe80, performed the best.
   - Maximum cutting force remained constant throughout the testing period of 200,000 strokes. Rejection force was low and increased slightly during the test while retraction force remained nearly constant throughout.
   - The forces observed when using the TiN+WOx coating are smaller than those observed for an uncoated tool. The cutting force, rejection force and retraction force decreased by 4%, 80% and 86% respectively.

2. Dry blanking of 1 mm thick CuZn37 brass alloy
   - Experiments with an uncoated tool had to be aborted at 80,000 strokes due to total fatigue of punch contact surfaces.
   - Cutting force, rejection force and retraction force can all be decreased using a newly developed carbon based coating. The carbon-based coating allows full testing of the tool over 200,000 strokes.
   - Additional tests with carbon-based coatings will be conducted.


   - Coefficient of friction is determined using aluminum, copper and carbon steel workpieces sliding over coated tool surfaces without lubrication.
   - Cemented tungsten carbide (WC) tools coated with TiC, TiN, TiC+TiCN+TiN, TiAIN and DLC (diamond like carbon) are compared using a ring compression test.
   - Most workpiece specimens are tested under the as-machined condition on a 60 ton press with an initial speed of 150 mm/sec. Some specimens are oxidized at 1100°C in air to test the effect of an oxide layer. Tool surfaces were polished and all surfaces were cleaned with benzene prior to the experiments.
   - Experiments show that for aluminum, the DLC coated tool performs best and lowers the coefficient of friction from 0.095 in the non-coated tool to 0.076 (25% relative decrease in coefficient of friction). Figure 5.1.9-1 shows the effect of reduction in height on the measured coefficient of friction for the non-coated base material and DLC coated tool with aluminum billet.
Figure 5.1.9-1: Effect of reduction in height on coefficient of friction

- Figure 5.1.9-2 shows that the existence of an oxide layer on the billet surface nearly doubles the coefficient of friction. Therefore, it seems essential to remove oxide layers prior to forming without lubrication.

Figure 5.1.9-2: Effect of oxide layer on friction with coated tools

- Results show that friction increases linearly with surface roughness almost irrespective of the tool surface material. The results also show that copper may be formed without lubrication if the tools are coated with TiC or TiN and polished to mirror surfaces.

5.1.10 “Development of ceramic coatings by pyrolysis, especially laser pyrolysis of organo-metallic polymers (Research)” Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

- Aim of the project is the development and characterization of ceramic coatings on various substrates.
- Polysilazanes are used as precursor materials, which are applied by simple painting techniques such as dipping or spraying.
• Precursor is transformed into Si-C-N ceramics by laser radiation.
• This technique allows low melting alloys to be coated without affecting the substrate.
• Provides high hardness and good chemical resistance.

5.1.11 "Advanced surface texturing of hard coated cold forging tools (Research)" Prof. M. Geiger – Institute for Manufacturing Science, University of Erlangen-Nuremberg, Germany.

• Topography of cold forging tools, coated either by PVD or CVD, is textured by means of excimer laser radiation to improve its tribological behavior and to increase tool life.
• Production tool life increased by 40% compared to non-textured tools.
• Further modifications to the texture were performed and the tool life increased by 80% compared to non-textured tools.
• Use of textures with improved geometry could potentially lead to tool life increases of up to 200%.


• The development of a coating capable of performing preservation, lubricant, and primer (PLP) functions, and thus eliminating several steps from the conventional deep drawing process is discussed.

![Figure 5.1.12-1: Conventional deep drawing vs. PLP deep drawing](image)

- It is desired to develop a heavy metal free liquid product such that scratches obtained during material handling or storage can be covered easily.
- Tests run with each PLP coating include:
  1. Oil content in aqueous phase determination.
2. Viscosity determination.
3. Tacky transition temperature after thermal curing determination.
4. Tacky transition temperature after UV curing determination.
5. Number of MEK double rubs to reach substrate determination.
6. Gelatin time determination.
7. Adhesion determination.
8. Surface energy determination.
9. Limiting drawing ratio determination.

- The desired properties of the PLP coating include:
  1. Tribological performance equal or better than traditional lubricants.
  2. Good wetting of metal surface.
  3. Appropriate viscosity.
  4. Curable.
  5. Compatible with primer resins.
  7. Economically favorable.

- PLP’s based on Edenol B316 and Edenol B316/Pripol 1040 met these requirements. Thus, they could be used to simplify metal working processes such as deep drawing.

5.1.13 “Wear Test for Deep Drawing and Stretch Forming Dies (Research)”
Prof. P. Groche / PtU – Institute for Production Technology and Forming Machines, Technical University Darmstadt, Germany.

- Forming of high strength steels, Al alloys and coated sheet material requires the development of new die materials, die coatings and lubricants.
- The objective is to increase the robustness of the process, improvement of the formed component and selection of optimum die materials and coatings.
- A strip drawing system, including bending, has been developed and used for experimental studies to evaluate die life, surface quality of deep drawn parts and the variations of friction, surface finish and forming force.


- Ceramic and diamond like carbon coated tool surfaces and chromium free lubrication primers applied to aluminum sheets are studied as means of reducing lubrication in aluminum deep drawing.
- Wear and friction tests are performed with both coated tool surfaces and coated sheet surfaces by simulating the critical contact at the draw-in radius with the TNO slider on sheet tribometer.
Coatings that performed well according to the tribometer are also tested in industrial deep drawing runs.

The results between the tribometer and the industrial tests are consistent.

According to the tribometer and industrial tests, CVD diamond like carbon coating applied to the tool offers the best possibility of drawing both 1050 and 5754 aluminum alloy sheets without lubricant.

Also, PVD CrN coating applied to the tool offers the possibility of reduced lubricant when drawing 1050 aluminum alloy sheets.

According to the tribometer, the chromium free lubrication primer's performance resembles that of a medium drawing oil.

Figure 5.1.14-1: TNO slider on sheet tribometer


Because friction in sheet metal forming is dependent on the surface topography of both the tool and workpiece and because ceramic tools show marked improvement in tool life due to their high wear resistance, the possibility of using excimer laser radiation to produce micro textures in ceramic tools in order that they support hydrodynamic lubrication and reduce friction is discussed.

With excimer laser material processing, depth profiles in accordance with hydrodynamic theory are produced in the ceramic.
Figure 5.1.15-1: Excimer laser material processing

- A strip drawing testing device is then used to evaluate the coefficient of friction.

Figure 5.1.15-2: Strip drawing testing device

- The results are comparable to that predicted by hydrodynamic theory.
- Friction decreases with increasing depth of the textures up to 10 μm and decreases with increasing length of the textures.
- In addition, friction decreases with increasing drawing velocity and increasing with increasing normal pressure.
- Possible benefits include:
  1. Reduced friction.
  2. Improved lubricant use and minimized lubricant expense.
  3. Reduced tool wear.
  4. Improved process conditions and forming of more complex parts.
- Increase in net product both economically and ecologically.

5.2 Process Monitoring and Control

5.2.1 Tomov, B., Chodnikiewicz, K., (1998) “A mechanical device for measuring the displacement and rotation of a blanking or forging
A simple device that can establish the ram deflection during a presswork or forging cycle is developed. The device operates by measuring the coordinates of four points during an idle cycle and a work cycle. Four points are used to describe a plane and a vector normal to the plane, which allow specification of the ram displacement and rotation. The device consists of an upper plate fixed to the ram, lower plate fixed to the press bed and four “markers”. This method appears to be suitable for use in small shops.


At operating speeds greater than approximately 200 strokes per minute, mechanical presses exhibit dynamic effects that may influence the process conditions. In order to maximize the advantages of high speed presses and maintain reproducible part quality, it is necessary to monitor and understand these dynamic phenomena.

A series of experiments was performed with a mechanical high-speed press. This press is capable of reaching stroke rates up to 1200 SPM. The goal was to simulate several real process loading conditions by means of calibrated load cells, in order to monitor the dynamic behavior of the press. Changes in shutheight, load, and slide deflection were measured for different press speeds and tonnages. By damping the impact on the load cells, the shape of the load-time curve was made to better represent that of a real process such as blanking.

Results of these tests help to improve understanding, allowing future press applications to be set up faster and more precisely. The information gained from this study will help improve the practical utilization of high speed presses by a) improving instrumentation and monitoring techniques, b) facilitating rapid and precise tool set-up, and c) incorporating dynamic considerations in process and tool design.

The following operational conditions were investigated a) influence of dynamic loading effects, b) parallelism between slide and bolster, and c) change in shutheight under various operating conditions.

Experiments showed that the dynamic behavior of a mechanical high-speed press is affected by many different factors. The complexity of the system and limitations in the ability to control all of the variables complicates attempts to isolate and analyze individual sources of dynamic response.

Tests under loading conditions showed that it is possible to simulate several real processes by means of calibrated load cells. By damping
the impact on the load cells, it was possible to achieve a load-time curve similar to a blanking operation. The changes of the peak load over the speed range of the press are mainly influenced by the press itself and by the dynamic part of the load. The load increase at higher speeds reflects the short deceleration time of the whole mass of all moving parts of the press, resulting in higher dynamic forces.

- Results show that investigating the performance of a high-speed press under different speed and loading conditions helps to demonstrate and understand the dynamic effects. The complex interaction of these effects may dramatically influence the quality of the parts produced and the requirements placed on a press and tooling.


- This paper summarizes the results of testing the performance of in-die sensors for controlling the stamping process. Piezo based as well as strain gage based in-die sensors were mounted at different locations within a progressive die. These signals were compared with load curves of press frame mounted sensors and the acoustic emission acquired from a triaxial acceleration sensor.

- The signals acquired from the different in-die sensors at the different mounting locations showed all the different phases of the process. It was shown that changing process variables such as punch-die clearance, material properties, stroke rate and punch-die alignment results in different load-stroke curves. Based on these results it could be concluded that in-die sensors provide the most detailed information about the process.

- Experiments were conducted with a progressive die on a 60 ton Minster Pulsar high-speed press. A five station progressive die designed for washer blanking was used in the experiments. Figure 5.2.3-1 shows the tooling and stamped parts at each location.
Experiments used strain gage and piezo-electric load sensors. Strain gage based sensors were also mounted to the press uprights. A triaxial acceleration sensor was mounted to the lower die to monitor the acoustic emission during the blanking process. An angular displacement transducer was connected to the crank shaft in order to monitor the crank angle and calculate the punch position.

From the experiments, it was concluded that continuous load monitoring through the stroke provides detailed information about the different stages of the process. This is a prerequisite for producing consistent part quality, detecting process trouble and recognizing process trends.

It can be concluded that piezo and strain gage in-die sensor signals correlate very well and that these sensors can be used to monitor the different stations of a progressive die individually. The strongest and cleanest load signal was acquired when placing the sensors as close as possible to the point where the load is generated (i.e. above punch head).

It was possible to detect problems such as poor punch-die alignment and changes in material properties. Comparing the load signal of an in-die sensor with the one of a press frame sensor and an acceleration sensor showed that the in-die signal contained much more detailed information about the process. The frame and acceleration signal show major process changes, but they are simply a superposition of all the operations performed in the die. They are also influenced by the press dynamics.

Since the in-die sensors responded the best to small process changes, they have the greatest potential for process control.

The work performed indicates that monitoring and controlling a stamping process directly inside the die is a very powerful tool to assure consistent part quality and reduce the production of scrap parts. Since the sensors are easy to retrofit into an existing die and are not very costly, they could be applied in a wide field of stamping applications.
5.3 Prototyping and Rapid Tooling


- Rapid tooling is used to produce a left-hand guard part for a lawn mower.
- Two tools are produced using rapid prototyping
  1. Stereolithography technique with nickel electroforming process
  2. Stereolithography QuickCast pattern infiltrated with aluminum-filled epoxy designated as QuickTool
- QuickTool’s material is not very durable; while the nickel electroformed tool is much more durable and can withstand more extreme working conditions.
- Nickel electroformed tool performs reasonably well but was scratched by a wrinkled blank. Wrinkling could not be avoided because the die was designed without a blank holder.
- QuickTool die was designed with a blank holder. Therefore, the part quality produced by the QuickTool design was much better.
- Both tool types seem to be potential tools for sheet metal forming.
- QuickCast tool is more economical in terms of development and production.


- A quick method of producing rapid tooling with properties similar to hardened tool steel is investigated. The tooling, which was fabricated from metallic and ceramic powder, has tailored mechanical properties and takes one week to manufacture. A picture of the final tool is shown in Figure 5.3.2-1.
Steps in the manufacturing process are as follows:
1. Design a model of the tool in a solid modeling package.
2. Build the model using a rapid prototyping technique such as stereolithography.
3. Make a silicon rubber negative of the model.
4. Prepare molten slurry of molten polymers and a blend of powdered metal or ceramic materials.
5. Pour slurry into silicon rubber mold and allow it to solidify.
6. Remove part from silicon rubber and remove binder polymers.
7. Sinter the green part to fuse metal or ceramic powders together and eliminate porosity.
8. Polish to obtain a desired surface finish.

Results show that some mechanical properties were comparable to hardened tool steel. The tool material has good wear resistance but impact properties must be improved. The surface hardness obtained was 35-40 HRC while optimization of blend powders could increase the hardness to 50+ HRC. The transverse rupture strength was 1150 MPa.

It is thought that the tool life will be comparable to tool steel; however, life cycle testing is required.

The process must be replicated to determine dimensional stability and shrinkage. An evaluation of part sizes that can be produced must also be done.

Experimental work to reduce shrinkage is currently under way.


Recent developments in rapid production of tooling used for low volume sheet metal forming are summarized.
• Recently, high-speed milling has been applied to ferrous die steel due to the development of a highly durable cemented carbide tool coated with ceramic.
• Milling speed has been further increased by the development of a high-density sintered cBN tool with high heat resistance.
• Coated carbide tools for high-speed milling are being applied in the manufacture of forging dies. The bottom corners of die cavities can be machined with ball end mills that have small diameters.
• Tools made by high-speed milling can be used for medium and mass production.
• With the age of ultra high-speed milling projected to arrive in the near future, it is expected to become a rival against simple and quick forming tools.
• Lamination of thin metal sheets, which are cut by lasers, can be used to produce dies; however, the process needs improvement.
• The production of dies by low melting point alloy casting has been developed. A punch, which is machined from wood, is covered with a heat resistant silicon rubber sheet. A low melting point alloy is cast over this to produce the metallic lower die, which as adequate strength and minimal shrinkage. Auto manufacturers currently employ this technique in the production of prototype forming dies. Figure 5.3.3-1 shows a schematic overview of the process.

![Figure 5.3.3-1: Low melting point alloy casting process](image)


• Direct metal laser sintering (DMLS), which was developed by EOS GmbH of Munich, Germany, is evaluated as a means of producing rapid tooling.
• A sample part, produced from a mixture of nickel, bronze and copper-phosphide, is infiltrated with epoxy and evaluated. Dimensional accuracy, surface roughness, impact toughness, hardness and strength are assessed.
Dimensional inaccuracies were observed, the largest being 0.082 mm. Inaccuracies in cylindrical features, which may be attributed to unequal shrinkage of the part, were observed with errors ranging from 0.025 to 0.34 mm.

The hardness of the sample part was measured at 65-69 HRB.

An impact toughness of approximately 4 Joules, which is quite low, was measured.

The surface roughness of the epoxy-infiltrated part was in the range of 4 to 7 μm, which is comparable to a rough EDM surface.


Characteristics of two rapid tooling methods are described.

The first group, which is known as “firm tooling”, includes less expensive methods with shorter lead times and is appropriate for tool validation before changes become costly.

• Copper PA, a metal-plastic composite designed for low volume applications, can be used to fabricated parts from common plastics.
• The inserts, which are sealed with epoxy and finished with sandpaper, are backed up with a metallic alloy and are easy to machine.

The second group, known as “hard tooling”, includes manufacturing of inserts for pre-production and production tools via the RapidTool™ process, which employs the selective laser sintering (SLS) technique to build the inserts. A die casting tool produced from RapidTool™ inserts is shown below in Figure 5.3.5-1.

Figure 5.3.5-1: Die casting tool produced from RapidTool™ inserts

• LaserForm™, the latest material developed for RapidTool™, is a powder made of 420 stainless-steel-based particles coated with a thermoplastic binder. LaserForm™ is used in the RapidTool™ process to fabricate tooling inserts.
• Selective laser sintering is used to build “green” inserts.
The green part is converted into a fully dense metal part by infiltration with molten bronze.
The final inserts, which are 60 percent stainless steel and 40 percent bronze, can be finished by any machining technique.


A study on a process combination of wire welding technology using CO2 laser radiation with milling was completed with the goal of producing a prototype for injection molding.
Rapid prototyping is performed using wire metallic materials, which are melted through laser heating and arc welding. Cutting is used to enhance the surface finish once the shape is formed.
Shapes that were impossible to manufacture with cutting alone can be formed by combining layer integration and cutting technologies.
Precision and surface accuracy can be achieved.
The use of wire, compared to powder, gives rise to a simple feeding mechanism and higher deposition rate.
The prototyping equipment consists of a CO2 laser or arc welding equipment, a milling machine and a wire-feeding device, which provides a steady feed of wire via servomotors.
Nitrogen gas is used to prevent oxidation during layer integration.
Quality of the end product is influenced by process variables such as welding wire type and size, type of gas used, base material, welding frequency, welding voltage, current, laser power, wire feed rate, distance between beads, welding speed, cutting tool radius and cutting speed.
Experimental results show that bead size varied inversely with table speed (increase in table speed results in a decrease in bead size) and directly with wire feed rate (increase in wire feed rate results in an increase in bead size).
Tensile test results show that the wire used in welding (AWE ER 70S-6 carbon steel wire of 0.9 mm diameter) behaved similar to conventional carbon steel.
Production time needs to be optimized by improving table speed and processing at higher laser powers.
FEM analysis is required to test for residual stresses.

Attempts were made to improve the heat resistance of rapid prototyping models for use with thermal spraying of high melting point alloys.

A high heat resistant mold is manufactured from the master model using the following process steps (see Figure 5.3.7-1).
1. A silicon rubber mold is made from the master model.
2. An original mold is made from the silicon mold by powder slurry casting of metallic and ceramic powders.
3. The original mold is baked and sprayed with SUS431 spray powder, which provides good corrosion and wear resistance.
4. A backup is made by casting Bi-Sn-Sb alloy, which yields high precision with minimal thermal shrinkage, over the original mold.
5. The metallic mold is obtained by breaking the sprayed original pattern and removing the backup.

![Figure 5.3.7-1: Heat resistant mold manufacturing process](image)

Results show that it is possible to manufacture spray tools with stainless steel and iron-nickel-chromium alloys from rapid prototyping models.


- Article describes optimization of the manufacturing of prototype tools for sheet metal forming with zinc alloys. The V-process, which enables a faster, cheaper and environmental friendly production process, is used in the production of sand molds.
- The V-process, shown in Figure 5.3.8-1, is a mold production process in which the casting mold is produced by the packing of mold sand without any chemical binders.
- Advantages of the V-process are a) environmental friendly b) low cost of molding material c) cheap model materials d) high dimensional accuracy e) possible low wall thickness f) low mechanical load of the molding box g) good working conditions and h) good surface finish (shot blasting can be omitted).
- Disadvantages of the V-process are a) high investments during small molding performance b) license costs c) high energy consumption d) dust problems when releasing from mold e) long cooling periods by the
high isolation effect of the mold f) anti-adhesion fluid needed and g) increased expenditure by air ducts.

- The procedure proved to be suitable for the casting of gray cast iron, nodular cast iron, steel, aluminum alloys and red brass.

Figure 5.3.8-1: V-process for sand mold production

- Model materials are wood, hard-resistance mold foam and others that are easily machined. Model material should possess low heat conductivity to prevent quenching of model foil (metallic materials are not suitable). Wood and plastic are preferred model materials. A smooth model surface is not required, as the foil will cover the model surface.

- Special thermoplastic foils, which evaporate during the casting process, are typically used. The foil should possess the following characteristics a) low melting point b) high and uniform elasticity after heating c) evaporation of the foil without hazardous exhaust gases and d) low cost.
- Fine granulated binder-free quartz sand with rounded edges can be used for all casting materials except steel, which requires use of olivine or chromate sand. Fine granulated sand is required to produce castings with good surface finish.
- The mold release agent functions to prevent melt penetration into the mold surface. Mold release agents should have the following characteristics a) should not disintegrate the foil b) good adhesion of the release agent to the foil c) thin layer applications d) quick drying process and e) low tendency to react with the liquid metal.
- Mold hardness and compressive strength both increase with increasing negative pressure (vacuum pressure).


- Solid freeform fabrication integrated with electroforming as a novel process for the generation of metal molds and EDM electrodes is presented.
- Figure 5.3.9-1 shows the production steps for the manufacture of an EDM electrode. A master model is built from CAD data using rapid prototyping techniques. Metalization is performed on the model’s surface to ensure that the model is electrically conductive. The metalized part is then electroplated with copper to the required thickness. Next, the master model is removed from the electroplated shell and the shell is backfilled.

![Figure 5.3.9-1: EDM tooling process](image)

- A similar process is used to generate mold tooling for injection molding (see Figure 5.3.9-2). A master model is metalized using nickel electroless plating to a thickness of 0.005 mm. The metalized master is then electroformed to the desired shell thickness. Separation is done by burning out the master and backfilling the shell.

![Figure 5.3.9-2: Mold tooling process](image)
The factors that affect accuracy of the final mold/electrode are a) accuracy of the RP master model b) electroforming thickness c) deformation caused by electroforming and d) thermal deformation during burn out of master and backfilling of shell.

Electroforming can achieve deviation between the master and the electroformed part as small as 0.0025 mm.

Thermal deformations caused by burning out the master and backfilling the shell are thus important sources of inaccuracy.

Rapid prototyping coupled with electroforming is capable of producing tools with better accuracy and finer surface finish compared to processes that bind metal particles.


An auto body consists of approximately 400 sheet metal parts with each part requiring a set of five to seven tools. Therefore, the cost of tools has a significant influence on the price of each car. Generally used cast iron tools guarantee outstanding quality but are time consuming and extremely costly to manufacture. For small batch production of 10,000 parts, conventional methods of die manufacturing are time consuming and expensive, which makes them uneconomical. The authors present a new method of die making using polymer materials for low volume production up to 10,000 parts.

Polymer materials offer very good tribological properties. The low friction can save lubricants and this is especially advantageous in aluminum, as the polymer does not tend to adhere with aluminum as metals do. Furthermore, stamping of prepainted sheets is possible because the polymer tool surface won’t destroy the sheet surface.

Polyurethane dies can be produced by machining or by casting. The first step is to mill the punch and the blank holder. The procedure is shown in Figure 5.3.10-1. The massive castings are made using commonly known technologies:

1. Coat the blank holder and the punch with wax layers of thickness same as sheet thickness.
2. The required die radius is added on the wax material.
3. A casing with desired dimension of the die is wrapped around the punch and the blank holder.
Figure 5.3.10-1: Set up for making polyurethane mold making

- Figure 5.3.10-2 shows the principle of Gel Coat Technology.

Figure 5.3.10-2: Manufacturing of polymeric die by gel-coat technique

- Figure 5.3.10-3 shows the principle of Cast Front Layer technology.

Figure 5.3.10-3: Manufacture of polymeric die by cast front technique
To evaluate the performance of the polymer die, wear tests and strip drawing tests are conducted on polymer dies using:

1. Aluminum sheet coated with
   - A dry film lubricant
   - An epoxide coating Bonazinc 2004
   - Electro Coat Replacement (ECR), which is a not conducting.
   - Parts coated with ECR have to be joined mechanically.

2. Steel sheet coated with
   - Dry film lubricant
   - Bonozinc 3000
   - ECR
   - Polyester coating

Wear tests concluded that polyurethane dies withstand ten thousand cycles of loading in stamping with minimum wear and are better than kirksite, which is used in prototyping. A significant decrease in wear was observed when using aluminum sheets with dry lube and zinc coated steel sheets.

When using polyurethane as the die material, friction under dry conditions is lower as the adhesion between the polymer and aluminum, polymer and steel is less compared to steel and aluminum in conventional dies. Use of dry lubricants further reduced the friction.

Deep drawn tests conducted using polymer dies confirmed the results of strip drawing tests. The maximum LDR of 2.4 was achieved for aluminum and steel sheets with dry lubricant using polyurethane dies.

Polyurethane material offers a potential alternative for manufacturing dies in small batch production. Use of coated sheets with dry lubricant provides the best interface conditions thereby eliminating the need of liquid lubricants in the process. Sheet forming polyurethane offers excellent characteristics, especially in aluminum, since there is a lower trend towards adhesion and no pickup, which restricts the use of steel dies.

- The objective of this study is to develop rapid tooling systems for deep drawing and stretch forming of sheet metal.
- The principle of the method is to assembly a punch or a die from sheet material that is laser cut, using the CAD model of the tooling, Figure 5.3.11-1.

![Figure 5.3.11-1: Die assembled from laser cut sheet material](image)

- To reduce the non-uniformity of the tool surfaces and obtain acceptable quality surface finish in formed parts, a layer material (rubber or plastic) of appropriate thickness will be used, Figure 5.3.11-2.

![Figure 5.3.11-2: Use of a rubber or plastic layer material](image)


- Manufacturing of steel tubes for pipelines by high pressure forming of welded steel sheets is examined.
- The process, which is suitable for conventional and high strength steels, can reduce transport volume if the tubes are formed at or near the jobsite.
Essential process parameters are a) sheet thickness b) blank geometry c) welding method d) working media (gas or fluid) and e) raw material.

Fluids like oil or water with emulsions are preferred for anti-corrosion properties.

Results show that a) it is possible to form tubes by pressurizing welded sheets b) welding method and blank geometry are important process variables c) reduction in transportation volume allows longer tubes to be manufactured at the jobsite.