Doctoral Theses at NTNU 2005:3

Dirk Nolte

Analysis of Aluminium Hot Forging

NTNU
Norwegian University of
Science and Technology
Doctoral thesis
for the degree of doktor ingeniør
Faculty of Engineering Science and Technology
Department of engineering Design and Materials

NTNU

Preface

This work was carried out at the Norwegian University of Science and Technology (NTNU), at Department of Engineering Design and Materials over a three-year period from 2001 to 2004. It was performed under the NorLight programme. The financial support from Raufoss Technology AS and the Norwegian Research Council (NFR) through the Compform-project is greatly acknowledged.

The main aim of the study was to gain a better understanding of aluminium flow behaviour in closed-die hot forging and the effect of different process parameters using experiments and computerised finite element simulation. Advanced grid pattern technology and latest computer codes are evaluated and used.

This thesis is mainly composed of four parts: the first chapter is devoted to give a short introduction to the area of research. The second and third chapter are devoted to sum up the results organised in areas of interest. The final chapter contains research results in form of prepared papers.

I wish to express my deepest gratitude to my supervisor Professor Henry Valberg for guidance throughout this work, scientific support, for valuable advice and for inspiration. Further, I would like to thank Professor Ola Jensrud and his colleagues for providing me information on industrial aspects and test material.

I am very grateful to all my colleagues at NTNU supporting me with ideas and helpfulness, especially Dr. R.K. Uyyuru, H. Mjøen, L. Bjørkhaug and E. Hovda. I wish to thank the staff at NTNU, especially Wiggo Darell and Tor Samdal for their help. In addition, I wish to thank the staff at SINTEF, especially Robert Faltval, Martin Lefstad and Shahriar Abtahi. I am very grateful to Chris Margaret Aanondsen for editing this thesis.

Contents

List of papers

Paper I: Dirk Nolte, Henry Valberg:
Surface extension and material flow in hot aluminium forging investigated by use of FE-simulations and experiments,
6th International ESAFORM Conference on Material Forming, Sorrento, Italy, 2003, pp. 947-950.

Paper II: Dirk Nolte, Henry Valberg:
Material flow analysis in hot aluminium forging with special emphasis on the conditions in the flash gap,
New developments in Forging Technology 2003, Stuttgart, Germany, 2003, pp.389-409.

Paper III: Dirk Nolte, Henry Valberg:
Surface extension and material flow in axisymmetric hot aluminium forging,
7th ESAFORM Conference on Material Forming, Trondheim, Norway, 2004, pp. 627-630.

Paper IV: Dirk Nolte, Rama Krishna Uyyuru:
Review and Recent Developments in Physical Modeling of Metal Forming,
accepted for publication in the International Journal of Forming Processes (IJFP), IJFP manuscript number: 222, reviewed paper sent for publication.

Paper V: Dirk Nolte, Henry Valberg:
Traditional cylinder compression analyzed by help of internal stripe patterns,
submitted to International Journal of Forming Processes (IJFP), July 2004, IJFP manuscript number for review: 225.

Paper VI: Dirk Nolte, Henry Valberg:
Anisotropy effects in traditional cylinder compression of aluminium,
submitted to International Journal of Forming Processes (IJFP), October 2004.

Paper VII: Dirk Nolte, Henry Valberg:
Effect of workpiece anisotropy on metal flow and forging conditions in hot aluminium forging,
submitted to International Journal of Forming Processes (IJFP), October 2004.

Paper VIII: Dirk Nolte, Henry Valberg:
The Effect of Die Geometry on Forging Conditions in Axisymmetric Hot Aluminium Forging – an Example,
submitted to International Journal of Forming Processes (IJFP), October 2004.

1 Introduction

1.1 Background - general motivation

Today, aluminium is a common material for a various range of applications as e.g. building constructions, automotive applications, furniture production and much more. It is known that weight reduction can be achieved by using aluminium and the military industry used aluminium for over 50 years to build air plane body parts. A better understanding of the material and the forming processes lead to usage in more critical construction areas. Forgings offer a high strength-to-weight ratio, toughness, and resistance to impact and fatigue [ALT 86]. Therefore the forging process is often used to produce components of aluminium with a defined and exact geometry at high value of structural integrity as well as moderate production costs. Today, forged aluminium components are often used for applications relevant to safety like wheel suspension arms and steering components.

Aluminium is competing with other materials like high strength steels and composite materials, and it is necessary to find a good compromise between mechanical properties, formability, cost, the available production machines, weight, corrosion resistance, and so forth. There is a growing market of lightweight wheel chassis parts, aluminium in particular, during the last years. The opportunity for using forging seems promising if the costs are kept at a low level [JEN 03]. The marked demand for a rapid development of complex products at a competitive price is high. This necessitates fast and easy predictions of various process dependent parameters. A good understanding of material flow behaviour and of the effect and interaction of important process parameters on material properties may lead to good mathematical models and thus correct predictions to design optimized parts.

The forging process is often divided in several, sequenced forming processes, starting with the forging stock, forming intermediate shapes before attaining the final shape. The development of intermediate shapes to reach the final shape in forging is not an easy process when using classic tools as model material or just trial and error [JEN 03]. An important tool for optimization and development of forging processes are mathematical modelling and numerical simulation. Beside these developmental and optimising techniques, physical simulations either in laboratories or in industrial process chains are a necessary counterpart to prove analytical results and to reach the right conclusion.

Especially for applications with high load requirements it is absolutely necessary that mechanical properties of forged aluminium parts are precisely predictable. Wrong assumptions about material behaviour in forging may lead to macroscopic surface failures, as e.g. the folding of workpiece material or underfilled impressions. For components relevant to safety such failure is not acceptable. Mechanical properties of forged components, however. differ not only due to the variation of their final geometry. Their sensitivity to forging process parameters is significant. while the production techniques are often complex. Control and understanding of process variables at suitable forging process as well as skilful tool design is needed to achieve the optimal component property. One example is the contact developed between tool and workpiece which defines the material flow depending on friction conditions and arising temperature gradients. The final micro-structure at the surface of the component might be altered which is known to be of great significance to the mechanical properties [GÜN 90, GÜN 93, KOV 96]. A resulting poor surface region of the component may lead to a component failure. Crack growth due to defects on the surface is one of the main reasons for component failure [BOD 03].

Thus, a better understanding of parameter effects in forging and their interaction will lead to improved component properties in the future at lowered production costs and shortened development time. This is achieved by continuous development of mathematical models which validity is proven by experimental investigations. Even today, there is a lack of experimental analysing methods to achieve information on the material flow inside impressions and on the surface at the same time, when forming soft metals using lubrication at hot forging conditions. A further task is to get reliable information about surface strain, with high resolution that is not influenced by lubrication, amount of surface strain and/or contact pressure. In addition, the technique should not affect the material flow at any time and should be easy to use.

As mentioned earlier, the forging process offers deformation characteristics, which may improve the component properties if the process is well understood. There are many different forging methods, which can be classified in different ways. To get a detailed overview a lot of literature is available [BOD 03, LAN 85, ALT 86]. In the following chapter, a brief introduction is given to the so-called *open-die forging* and *closed-die forging* processes used in this investigation.

1.2 Basics of open and closed-die forging

Generally, forging can be performed either without previous heating of dies and workpiece or at elevated temperatures. If aluminium is deformed at temperatures and strain rates such that substantial recovery occurs during the deformation process, the process is called *hot forming*. Thus, temperatures at which deformation usually takes place are carried out above $0.6\ T_m$, where T_m defines the melting temperature of the used metal [ZAH 04].

A general classification of different forging processes is presented in Figure 1. In open-die forging the workpiece is formed by tools that are either flat, v-shaped or have a convex or concave shape. The product is shaped by a certain number of die strokes where the material flows unrestrictedly between the dies. The process is highly dependent on the shape of the tool, friction conditions at the die-workpiece interface, the compressive forces and the heating of the workpiece material [BOD 03]. The deformation is non-stationary and inhomogeneous.

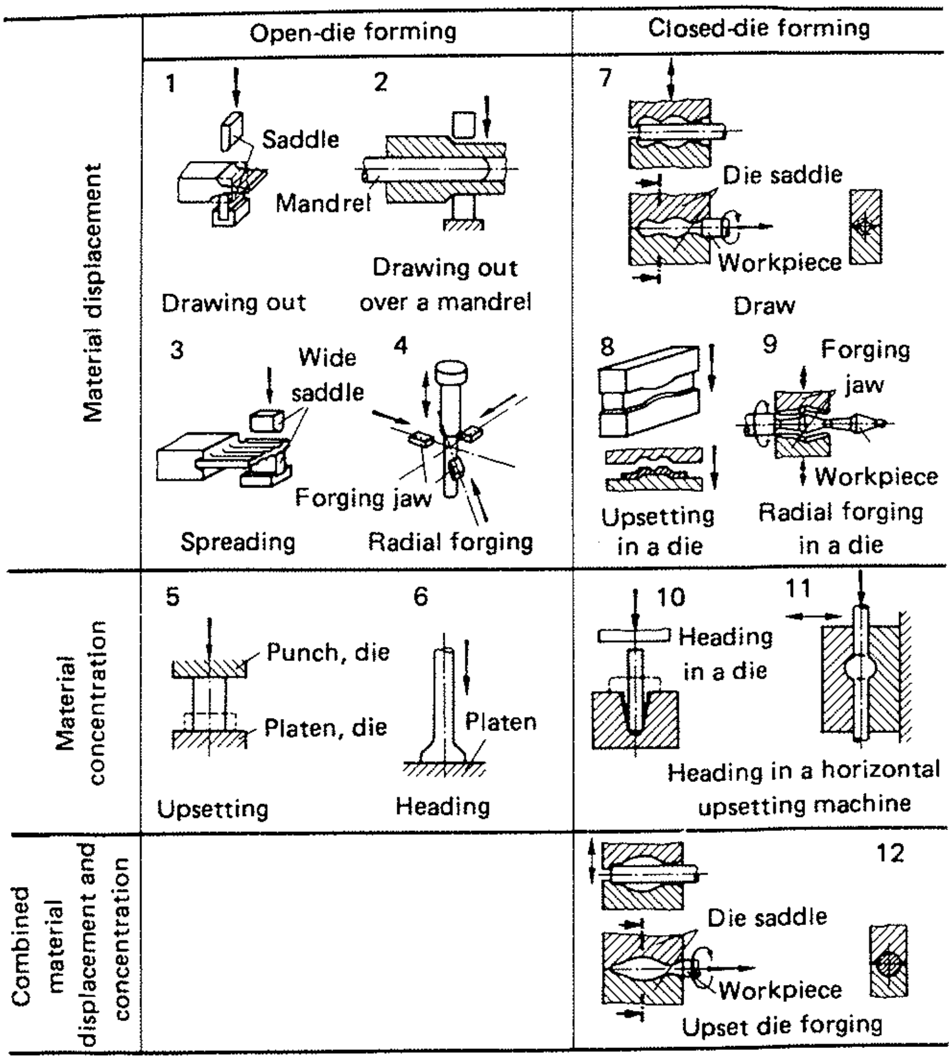


Figure 1. *Classification of different forging processes [LAN 85].*

Closed-die forging is characterized by dies having a cavity that is filled by workpiece material towards the end of forging. In closed-die forging without flash, a workpiece with carefully controlled volume is deformed by a punch in order to fill a die cavity without any loss of material. In closed-die forging with flash, the volume of the workpiece material is higher than the volume defined by cavities in the die. The excess material flows out of the die through a restrictive narrow flash gap and emerges as so-called flash. The geometry and the process conditions arising in the flash gap region are decisive for the die cavity filling process.

It is common that a part is forged in many steps. The main objective is to distribute the metal to avoid underfill and defects as e.g. folding to provide the necessary mechanical properties. In addition, material loss in forms of flash formation and wear in the finish forging cavity should be minimized [ALT 86]. Anyhow, costs of dies and press cycles to change material distribution of the workpiece are to relate to formability, costs of higher flash volume and excessive die wear. Here, the high cost of raw material is to be considered as e.g. the cost of aluminium in extruded and heat treated condition. Since friction conditions inside the impression and the flash gap region are directly related to the die cavity filling and the necessary amount of excess material in hot forging of aluminium, parameters controlling these conditions are of great interest to investigate. Parameters influencing the forging are given in Figure 2 [ALT 86]. In hot aluminium forging, the resulting metal flow shown in Figure 2 is again input parameter that controls the final microstructure defining the component properties, depending again upon temperatures, alloying elements, etc.

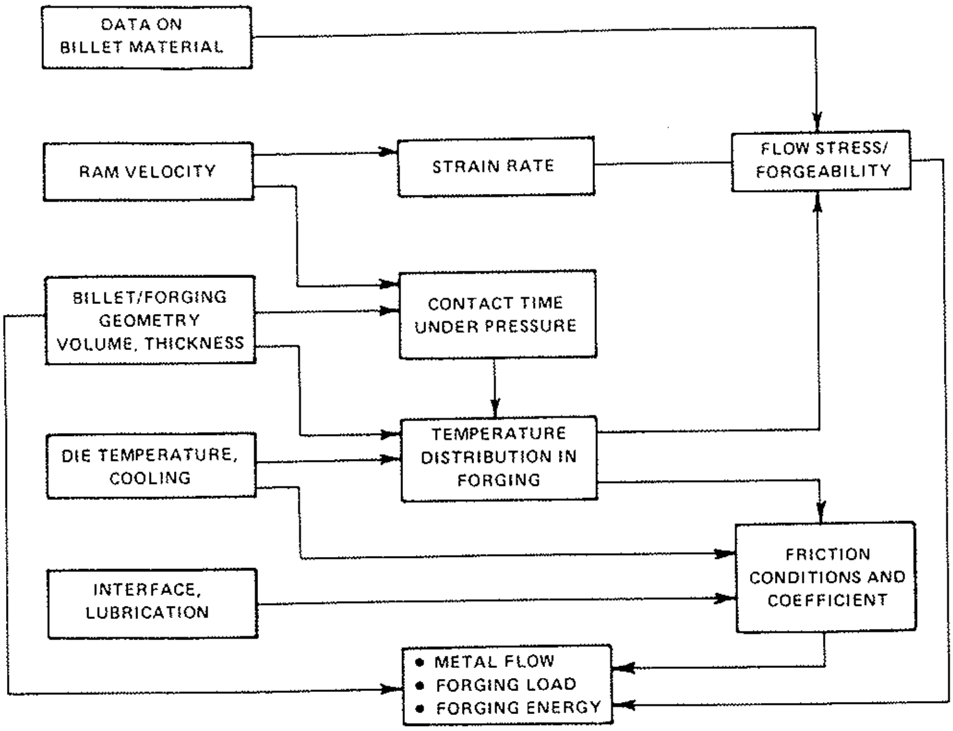


Figure 2. *Parameter influencing the forging result [ALT 86].*

Correctly designed and produced forgings are well suited for application in dynamically highly stressed constructions. Heat treatment of initial and final forging is of great importance to achieve the optimal properties of a forging. The initial workpiece is often made by casting and extrusion. One of the main issues is to adjust the thermo-mechanical process to meet mechanical requirements by controlling the microstructure of the material in the process chain from extruded bar to final shaped product. Anyhow, a distinct microstructure might be found inside the initial workpiece. The orientation of the microstructure is of great importance if the component is supposed to have the most excellent material property in certain directions. In some cases, a special machining of the forging stock becomes necessary to reach this goal. Examples of initial and final grain structures are shown in Figure 3 [LAN 85].

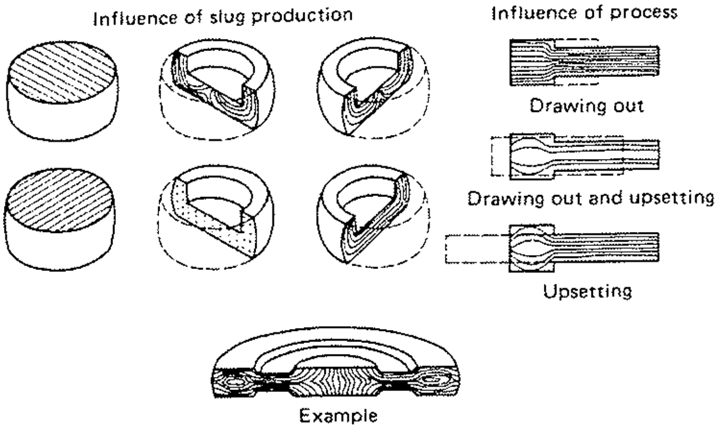


Figure 3. *Examples of grain structures at finished parts [LAN 85].*

Today, the classic process chain consisting of forging steps followed by heat treatment is optimised by integration of heat treatment with the forging to achieve optimal component integrity at shorter lead-time [JEN 03]. This requires that the process conditions as temperatures and deformations are well predictable and the process variations are controlled. Still, the long process chain from cast aluminium to final forging represents sources that might cause product property variations.

Plasticity theory deals with the calculation of stresses, forces, and deformation and provides approximate quantitative descriptions which are applicable to study forging [LAN 85]. For all investigations it is of main importance to know the flow stress $\sigma_f = f(T,\varepsilon,\dot{\varepsilon},S)$, T being temperature, ε true strain and $\dot{\varepsilon}$ strain rate and S the internal variables as the microstructure. To obtain these data, an open-die forging process may be used. The cylinder upsetting and the torsion test are common methods for determination of the flow stress at given conditions. Deformation characteristics might be studied for different material conditions, lubrications, temperatures, strain rates, surface finish etc. [KAL 84, ALT 86]. The resulting data are used to formulate flow rules and to find parameters used in mathematical analysing tools as analytical models and FE-simulations.

Thus, to develop analytical and numerical models of forging processes and to verify the results of different hypotheses, physical modelling and testing is an important tool both in research and industry. For precise mathematical modelling, boundary conditions, friction, heat transfer, etc. have to be described realistically. Experimental investigations along with finite element simulations are of utmost importance to obtain a fundamental understanding of forming and the influence of related parameters.

1.3 Available methods to analyse metal forming

To investigate forging processes, besides analysing the actual process, both physical modelling and mathematical modelling are often used to determine process parameter and their interaction. Here, processes are idealized to get information easier, and at defined and controlled boundary conditions.

Precise prediction of material flow, forces, stresses and temperatures is essential for the proper design of component and forging equipment. Behaviour of material during processing must be understood and parameters influencing final component properties taken into account. All analysing methods either help to understand material behaviour and main influencing parameters on forging result at given boundary conditions, and/or use classical mechanical laws to describe actual conditions as e.g. laws of continuum mechanics etc.

1.3.1 Mathematical methods

There are several mathematical methods available to investigate forming processes and to predict conditions arising as e.g. forces. Every method requires as input a) a description of the material flow behaviour as well as b) a quantitative value to describe the friction. The flow stress and friction must be determined experimentally and are difficult to obtain accurately. Thus, any errors in flow stress measurement, incorrect formulation of the material flow behaviour or uncertainties in the formulation and determination of friction factor are expected to influence the accuracy of the mathematical analysis [ALT 86]. Furthermore, in some mathematical methods physically arising conditions as e.g. temperature gradients inside the deforming material are not considered, which might lead to wrong assumptions regarding material flow.

The result of a mathematical analysis is dependent on the mathematical formulation of the material flow behaviour. Equations of a constitutive model for the material must be well formulated, having as main ingredients for an aluminium alloy a yield criterion, the associated flow rule and an isotropic hardening rule [LAD 04]. The formulation of improved yield criteria, as well as altered flow and hardening rules are still a subject of research and can be found reported in literature [LAD 04, STO 04, LIS 04, LAD 02].

Isotropic material behaviour is often assumed in analytical analysis to simply calculations and assures fast predictions of process conditions. Two important criteria for yielding under combined stresses are generally considered to be valid for metals:

(1) *Tresca yield criterion* [TRE 64]. Yielding is assumed to start when the maximum shearing stress, $\tau_{\max}$, exceeds a critical value, τ_{cr} which is equal to the yield stress in pure shear *k*:

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2} = \tau_{=cr.} = k \qquad (1)$$

where σ_1 and σ_3 are highest and lowest principle stress, respectively.

(2) *von Mises yield criterion* [MIS 13]. Yielding is assumed to start when the elastic shear distortion energy exceeds a critical value, and can be expressed in terms of stresses:

$$6k^2 = 2\sigma_0^2 = \left(\sigma_x - \sigma_y\right)^2 + \left(\sigma_y - \sigma_z\right)^2 + \left(\sigma_x - \sigma_z\right)^2 + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2\right) \qquad (2)$$

where σ_x, σ_y, and σ_z are stresses in direction of the three axes, x, y, and z which are orthogonal coordinate axes.

The assumption of isotropic material does not represent conditions present in forming processes where workpiece is often characterised by an anisotropic material behaviour. Therefore, yield criteria have been developed taking anisotropic material behaviour into account. An early example is the model for anisotropic material behaviour proposed by Hill [HIL 50] which is related to the criteria of von Mises. Again, the material's flow stress can be described along three orthotropic, principle axes, x, y, and z, and can be expressed by the function $f(\sigma_{ij})$:

$$2f(\sigma_{ij}) \equiv F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \qquad (3)$$

where F, G, H, L, M, N are parameters (usually considered as constant for a particular material) that characterises the material's current state of anisotropy. If F=G=H and L=M=N=3F, this criterion reduces to the von Mises criterion.

Hill's criterion has been applied in finite element modelling of metal forming analysis, especially in sheet forming, for many years [IVE 00]. The parameters used by Hill can be determined by tensile tests and are related to the R-value, which is often used in sheet metal forming to characterise flow behaviour in different tensile tests: e.g. $R = \varepsilon_w/\varepsilon_t = G/H$, where w and t refer to the width and thickness directions of a tensile specimen; for an isotropic material, R = 1. The yield loci resulting for a set of parameters that represent an isotropic material behaviour and, the yield loci for an imaginary material characterized by ~20% higher yield stress in y-direction in relation to the yield stress in x-direction is shown in Figure 4a) for cases of plane stress (σ_z =0).

Since Hill's anisotropic yield function was introduced, several other yield functions have bee proposed, e.g. Barlat and Lian [BAR 89], Hill [HIL 90], Karafillis and Boyce [KAR 93], Barlat [BAR 97], Banabic [BAN 03] and Bron [BRO 04].

In the field of sheet metal applications it is found that Hill's criterion seems to overestimate the effect of the R-value on the shape of the yield loci found in sheet metal forming [HOS 93]. Later, the three yield criteria proposed by Hill [HIL 50], Barlat and Lian [BAR 89], and Karafillis and Boyce [KAR 93] were found to be inadequate to describe the anisotropic flow properties of AA7108 and AA6063 extrusions which were analysed by means of uniaxial tensile tests [LAD 99a]. On the contrary, the criterion proposed by Barlat called "Yld96" [BAR 97] was found to give promising results when using AA7108-T1 alloy in tension tests to calibrate the plasticity model [LAD 99b]. A plot of yield loci found in this investigation of the alloy AA7108-T4 is presented in Figure 4b).

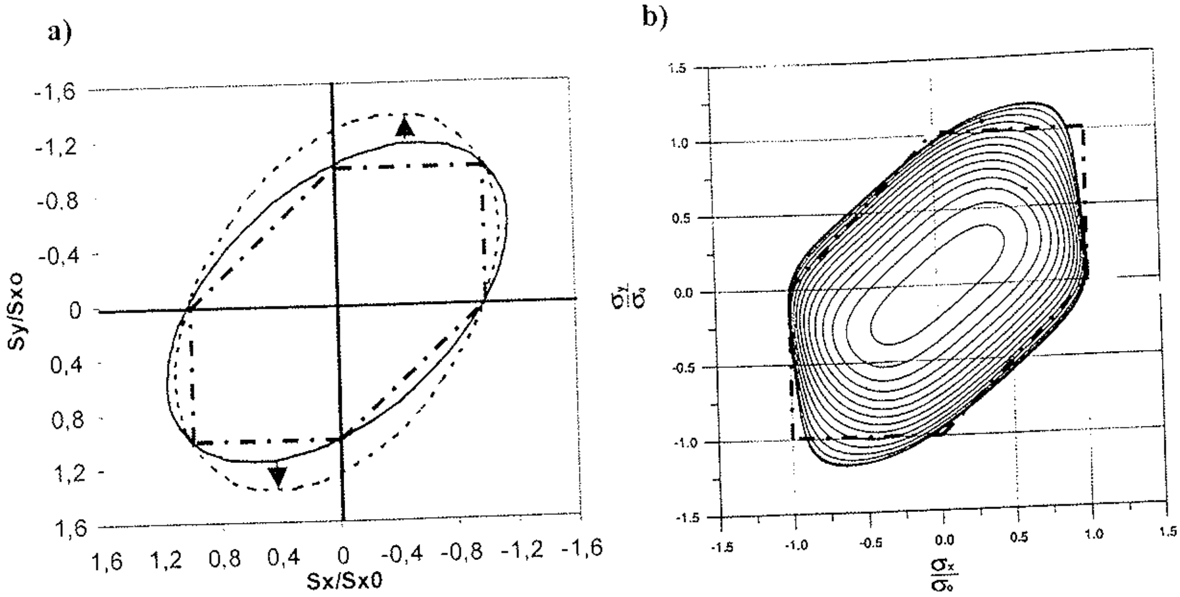


Figure 4. *(a) Plane stress (σ_z = 0) yield surface according to Hills criterion [HIL 50] for ~20% higher flow stress in y-direction with regard to x-direction (dashed), yield surface after von Mises (solid), Tresca (dash-dot) (b) Calibrated "Yld96" yield surface for AA 7108-T1. The contours represent levels of constant normalized shear stress σ_{xy} / σ_0 [LAD 99], yield surface after Tresca (dash-dot).*

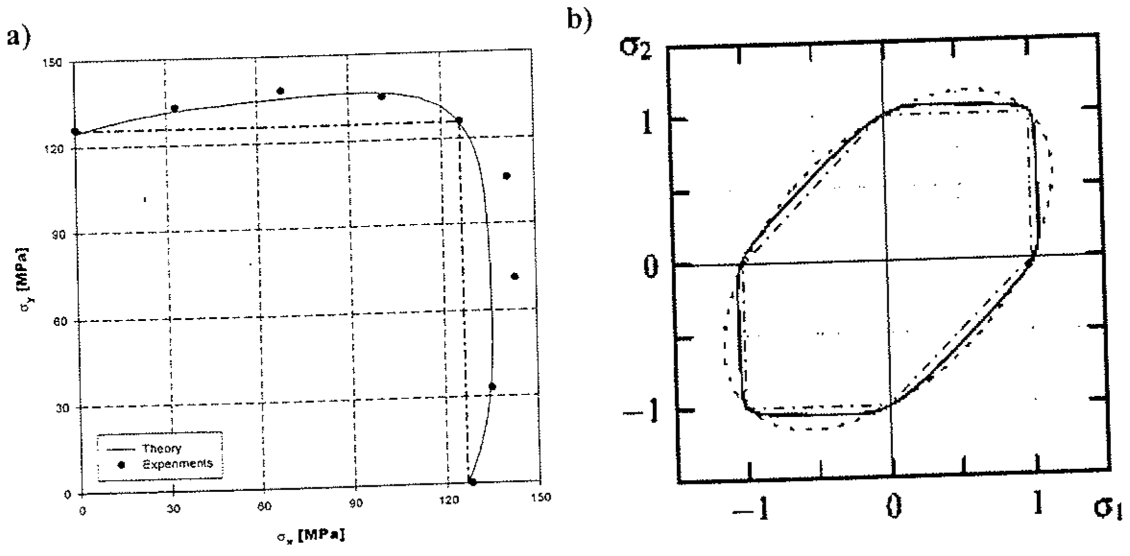
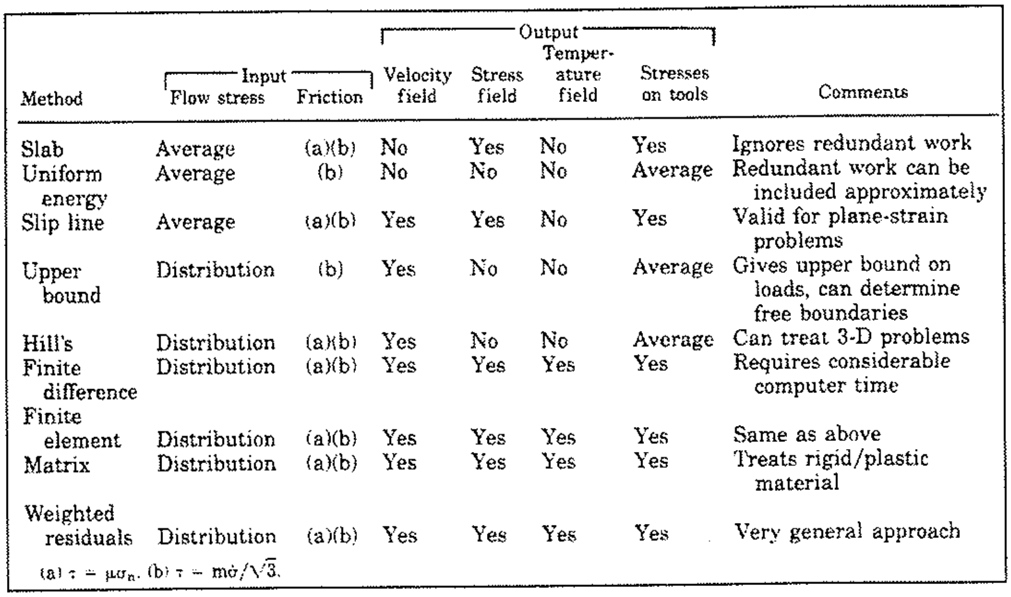


Figure 5. *(a) Yield surface according to Banabic [BAN 03] and experiments for A6XXX-T4, yield surface after Tresca (dash-dot). (b) normalized yield surface for 2024–T4 material (solid) compared to that of von Mises (dashed) [BRO 04], Tresca yield surface (dash-dot).*

Banabic [BAN 03] proposed a criterion which is derived from the one proposed by Barlat and Lian [BAR 89], and reported a comprehensive overview over the development of the different criteria. It has been found that the predicted yield surfaces for two materials, aluminium alloy A6XXX-T4 and a cold rolled steel sheet, are in very good agreement with the experimental data. The results for the investigation on A6XXX-T4 are shown in Figure 5a). The proposed criterion of Bron [BRO 04] is an extension of the functions given by Barlat et al. [BAR 91] and Karafillis and Boyce [KAR 93]. It is found that the proposed yield function is very accurate to describe the plastic anisotropy of various aluminium sheet samples. The result given as normalized yield surface for investigations of an AA2024–T4 material is shown for the particular plane (σ_x , σ_y) in Figure 5b).

Anyhow, most experimental investigation to evaluate the above mentioned yield criteria for anisotropic material behaviour are performed using different kinds of tensile and bending tests at cold forming conditions. There is a lack of evaluation of anisotropic yield criteria in the region of compression for materials in hot and cold forming. Here, especially for the kind of aluminium extrudates which are often used as workpiece material in hot forging processes.

Some major mathematical methods of analysis will be reviewed briefly and are described in more detail in literature [ALT 86, LAN 85, MIL 91, THO 65]. An evaluation of some mathematical methods is given in Figure 6.



	Input		Output				
Method	Flow stress	Friction	Velocity field	Stress field	Temperature field	Stresses on tools	Comments
Slab	Average	(a)(b)	No	Yes	No	Yes	Ignores redundant work
Uniform energy	Average	(b)	No	No	No	Average	Redundant work can be included approximately
Slip line	Average	(a)(b)	Yes	Yes	No	Yes	Valid for plane-strain problems
Upper bound	Distribution	(b)	Yes	No	No	Average	Gives upper bound on loads, can determine free boundaries
Hill's	Distribution	(a)(b)	Yes	No	No	Average	Can treat 3-D problems
Finite difference	Distribution	(a)(b)	Yes	Yes	Yes	Yes	Requires considerable computer time
Finite element	Distribution	(a)(b)	Yes	Yes	Yes	Yes	Same as above
Matrix	Distribution	(a)(b)	Yes	Yes	Yes	Yes	Treats rigid/plastic material
Weighted residuals	Distribution	(a)(b)	Yes	Yes	Yes	Yes	Very general approach

(a) $\tau = \mu\sigma_n$. (b) $\tau = m\bar{\sigma}/\sqrt{3}$.

Figure 6. *Evaluation of some numerical methods applied in metal forming [ALT 86].*

Slab analysis

The foundations of this solution technique were developed in 1925 by Siebel [SIE 25] and von Karmann [KAR 25] in connection with the rolling process. The slab method of solution assumes that the stresses on a slab perpendicular to the flow direction are in principal direction. The stresses are not allowed to vary on this slab. A slab, straight or curved, of infinitesimal thickness is selected parallel to this plane at an arbitrary point in the deformed metal. A force balance is made on this slab that will result in a differential equation of static equilibrium. The differential equation is then put in integrable form and both analytical and graphical techniques of integration are used. Introduction of the boundary conditions determines the forming forces and gives other pertinent information [THO65]. It should be remarked that the slab analysis usually leads to average forming stresses. For improved analysis using this method, corrections for geometry effects, as e.g. bulging in cylinder compression should be considered and taken into account, as done by e.g. the modified slab method from Ettouney [ETT 84].

Using the slab method, processes as simple plane strain and axisymmetric compression with friction are analysed but also more complex forging processes. There have been attempts to predict forces arising in more complex forgings by using computer simulation of the Modular Slab Method (MSM) [MIL 91]. The entire forging is then divided into different deformation units or zones at different stages of deformation, see Figure 7. The stresses and loads are calculated for each zone by considering that the strain distribution must be continuous. The technique can be used for only one part at a time, requiring a separate program, and therefore does not recommend itself to general application.

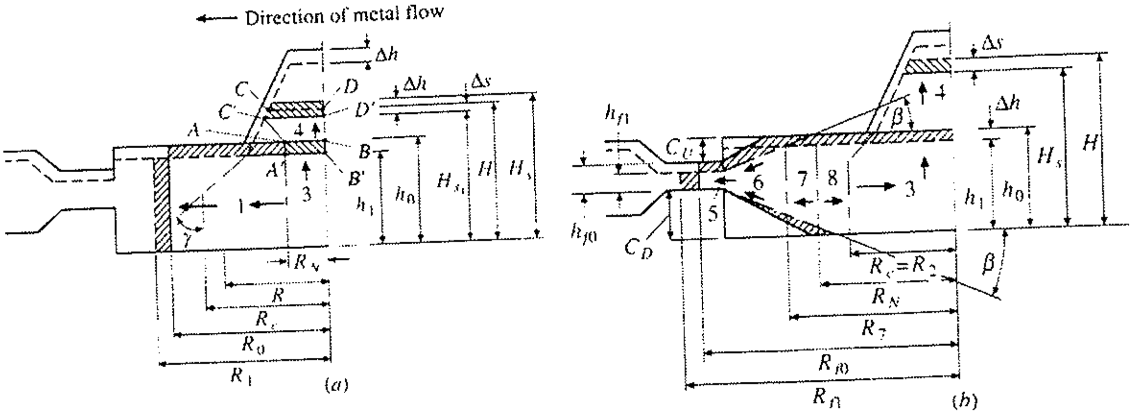


Figure 7. *Example of forging divided in several deformation unit and steps, here two forming steps a) and b)[MIL 91].*

Slip-line field method

After a historical evaluation by Thomsen [THO 65], the slip line method was apparently introduced by Hencky [HEN 23]. Many investigators since then have contributed to an increased knowledge of slip lines [PRA 23, HIL 50, LEE 52, BIS 58, GRE 55]. A method of introducing work hardening into slip-line analysis was also suggested [OXL 57].

A slip line field is a two dimensional vector diagram which shows the direction of the maximum (or minimum) shear stress at any point along the line. The slip line field is always a network of lines crossing each other at right angles. The lines have the property of satisfying static equilibrium, the prevailing yield condition, and a possible flow field everywhere in the plastic zone of the material being deformed without any reference to the plasticity equations and strain rates [MIL 91]. When elastic strains are neglected, calculations may be made for hardening as well as non-hardening materials. An assumption of a constant yield stress, however, leads to the simplest results. The method will at least provide an estimate of both the stress and velocity field. In comparison to a standard upper bound analysis, a firmer knowledge of the strain and strain rate history for a particle can be gained, Furthermore, by obtaining knowledge of the flow line of the material, one will also be able to calculate changes in temperature [STØ 03].

Before the finite element method started to spread to a variety of engineering and physical science disciplines, the slip line technique applied to plane strain was claimed to be perhaps the most successful, detailed and useful technique for analysing models of metal forming processes [MIL 91].

Upper bound analysis

This method utilises the extremum principle involving the method of virtual work [MIL 91]. The overall deformation zone is divided into a number of smaller zones within which the velocities of material particles are continuous. But particle velocities in adjacent zones may be different. However, just as in slip line analysis, at the boundaries between the zones, or between a zone and the die surface, all movement must be such that discontinuities in velocity occur only in the tangential direction [KAL 84]. A kinematically admissible velocity field is constructed and the loads are calculated to cause the velocity field to operate.

In this kind of analysis the total power consumed in an operation is the sum of the following: a) *ideal* power of deformation b) power consumed in *shearing* the material along the velocity discontinuities and c) power required in overcoming *friction* at the die-workpiece interfaces. In the final analysis, a velocity field that minimises the total calculated power is taken as the actual one and is subsequently compared to experimental data [KAL 84].

The upper-bound solutions overestimate the load and the results are often only of practical interest in metal working operations. The use of the upper bound method has been limited to simple metal working problems, mainly because of the difficulties involved in finding a sufficiently broad class of admissible velocity fields, or to describe complicated metal flow problems. Furthermore, once a class of admissible velocity fields is chosen, the solution becomes fixed [MIL 91]. Recent research, however, proposes kinematically admissible velocity fields suitable also for the open-die forging of a general non-axisymmetric shape [KWA 02].

Finite-element method

The use of digital computers increased the application of finite element method (FEM) in the 1960s, and has spread to a variety of engineering and physical science disciplines in the last decades [KOB 89]. It seems the first attempt to solve an engineering problem using this technique was by Courant already in 1940s [COU 43]. Finite element methods are predominantly used to perform analyses of structural, thermal, fluid flow and solid material flow situations. They are used mainly when manual calculations cannot provide accurate results. This is often the case when the geometry or process is very complex.

After Mielnik [MIE 91], the basis of the FEM is the representation of the body (or structure) by a contiguous assembly of subdivisions or sub regions called *elements*. In a continuum, the body is divided into a finite number of such elements in such a manner as to provide ease of calculation and to obtain the required information. This process of selecting only a discrete number of points by dividing the body into elements is called *discretisation*. One of the ways to discretise a body or a structure is to divide it into an equivalent system of smaller bodies or units. The assemblage of such units then represents the original body. Instead of solving the problem for the entire body in one operation, the solutions are formulated for each constituent unit and combined to obtain the solution for the original body or structure.

The above mentioned elements are considered to be interconnected at the joints which are called *nodes* or *nodal points*. Simple functions might be chosen to approximate the distribution or variation of the actual displacement over each element. The following six steps summarise the finite element procedure in setting up and solving any equilibrium problem [DES 72]:

1. Discretisation of the continuum: as described earlier, the body is divided into a system of finite elements.

2. Selection of the displacement models: the assumed displacement functions or models represent the actual or exact distribution of the displacements only proximately.

3. Derivation of the element stiffness matrix: this matrix relates the nodal displacements to nodal forces.

4. Assembly of the algebraic equations for the overall discretised continuum: in general, the basis for an assembly method is that the nodal interconnections require the displacements at a node to be the same at all elements adjacent to that node.

5. Solution for unknown displacements: the algebraic equations assembled in step 4 above are solved for the unknown displacements.

6. Computation of the element strains and stresses corresponding to the calculated nodal displacements: often, quantities in addition to nodal displacements must be determined as e.g. strains and/or stresses.

In the analysis of metal forming, plastic strains usually outweigh elastic strains and the idealization of rigid-plastic or rigid-viscoplasic material behaviour is acceptable [Mil 91]. The resulting analysis based on this assumption is known as the *flow formulation* [KOB 89], where the material is treated as *Non-Newtonian Fluid*. In other applications it is not possible to neglect the elasticity of a material. Thus, an elastic-plastic or elastic-viscoplastic material model is used, known as *solid formulation*. Here, the strain is separated into an elastic part and a plastic part. The elastic part is governed by Hook's law, while the plastic part uses the Prandtl-Reuss equations [LAN 85].

There are two modes of description of the deformation of a continuous medium, the Lagrangian and the Eularian. The Lagrangian description employs the coordinates of a typical particle in the reference (or un-deformed) state as the independent variables, while in the case of Eularian description the independent variables are the coordinates of a material point in the un-deformed state [KOB 89]. For the analysis of metal forming processes, flow formulation is based on infinitesimal deformation theory, while solid formulation considers finite deformation. The finite element mesh used in flow formulation is spatially fixed in the Eularian system and commonly used in analysis of liquid and gas flow, but also in metal forming analysis, as e.g. extrusion. In all other applications a Lagrangian system is used in the solid formulation. The computer code DEFORM^{TM} is based on a Lagrangian formulation and is used for investigations presented in this thesis.

The main advantages of the finite-element method are: (1) the capability of obtaining detailed solutions of the mechanics in a deforming body, namely, velocities, shapes, strains, stresses, temperatures, or contact pressure distributions; and (2) the fact that a computer code, once written, can be used for a large variety of problems by simply changing the input data [KOB 89].

1.3.2 Experimental methods

Cylinder compression test

The cylinder compression test is often used to analyse formability, flow behaviour and microstructure development at different conditions as e.g. temperature, geometry, strain, etc. Results might be used in different ways: either to predict conditions and effects at forming processes as e.g. rolling and forging, or to get parameter values for constitutive equations. As mentioned in the previous chapter it is of utmost significance to have precise descriptions of the material flow behaviour and boundary conditions, as e.g. friction. Mechanical properties of the deforming metal must be determined by experiments for different strains, strain rates and temperature. Cylinder compression at low friction is a common method to obtain necessary data. So-called *flow curves* are recorded and variables for mathematical descriptions determined. The yield stress is often expressed by the Norton-Hoff relation [MIE 91]:

$$\bar{\sigma} = f(\bar{\varepsilon},\dot{\bar{\varepsilon}},T) = K\bar{\varepsilon}^{n}\dot{\bar{\varepsilon}}^{m}e^{\frac{\beta}{T}} \qquad (4)$$

where K is a material constant, T the temperature, n is the strain hardening exponent, m the strain rate coefficient and $\beta = Q/R$ with Q as activation energy and R the universal gas constant. Aluminium at hot conditions does not depend much on strain but on strain rate due to temperatures being in a range where recrystallisation and recovery will take place. Thus, if no strain dependency is assumed n is assumed to be zero.

In the analysis of hot aluminium forming another material description is often used; the so called Zener-Hollomon relation, which is independent of strain [ZEN 44]:

$$\bar{\sigma} = \frac{1}{\alpha} \operatorname{arcsin} h \left(\frac{Z}{A} \right)^{\frac{1}{n}} = \frac{1}{\alpha} \operatorname{arcsin} h \left(\frac{\dot{\bar{\varepsilon}} e^{\frac{Q}{RT}}}{A} \right)^{\frac{1}{n}} \tag{5}$$

where A, n and α are constants for given material under given conditions determined by experiments.

Since workpiece in forging is often taken from extruded forging stock, flow stress is to be determined in different orientations inside the material in relation to the extrusion direction. The resulting flow curves are used to adapt parameters which define the mathematical predicted yield loci. Many mathematical yield criteria describing isotropic and anisotropic material behaviour were presented in literature in the last century. A few have already been described in chapter 1.3.1.

Ring compression tests

The so called *ring compression test* is a well known test method to evaluate friction conditions in metal forming. Basically, the test consists of compressing a flat ring-shaped specimen to a known reduction. Changes in internal and external diameters of the forged ring are very much dependent on friction at the tool/specimen interface [ALT 86]. The corresponding friction values can be read from calibration charts using the specimen height and change of internal diameter. Since the test was first proposed by Kunogi [KUN 54] it became very popular in spite of the fact that the test is not able to provide independent variation of the important tribological process parameters such as:

- contact pressure at die-workpiece interface
- extension of workpiece surface layer
- sliding length and sliding velocity of workpiece material along die surface

The popularity of the test is coupled with the easy performance. Usually, not even the registration of the load is necessary to determine the friction factor. The only parameters used to rank the frictional performance of a lubricant are reduction of ring height and change of internal diameter [HUN 95].

In some literature, it is stated that the barrelling of the ring material due to the interface friction does not influence the results strongly if lubrication is efficient [KAL 84]. On the other hand, authors rated the barrelling as one source of error when using calibration charts, calculated with help of the Upper Bound Extreme Theorem (UBET) [BUG 93]. Avitzur developed an upper bound method for the ring compression test, which considers the bulge in the ring due to friction [AVI 69]. Anyhow, in an investigation by Lee [LEE 72] a discrepancy of 10-17% was found between theoretical results taking the bulging into account, and experimental results. Today, the use of FEM-simulations is recommended to set up calibration charts leading to better accordance between experimental and theoretical results [BUG 93, GOE 91, TAN 98].

In a series of experiments using aluminium, copper, and steel at cold forming conditions the following reasons are given for deviations between theoretical and experimental results [HUN 95]:

- same lubrication does not provide same friction on different materials
- friction actually increases for increasing height reduction
- the used friction law does not describe real interfacial friction conditions

It is further stated that important parameters influencing the results are:

- surface extension in relation to height reduction
- normal pressure

In the literature it is stated that friction is dependent on the strain hardening exponent when using material at cold forming conditions. The dependency is called "complicated", assumed to be related to normal stress and investigated by the use of different ring geometries and calibration curves received from FEM-analysis [TAN 98].

The influence of anisotropy of the ring material is shown by Han [HAN 02]. Here it is found that a possible error in estimation of the coefficient of friction can be as high as 80% for a pronounced anisotropic material. A good overview over other parameters influencing ring compression tests is given.

At hot forming conditions it is found that calibration curves are affected by strain rate sensitivity of material at friction factors of $m = 0.15$ and higher. The curves are bounded on the upper end by zero strain rate sensitivity, or constant flow stress, and on the lower end by a strain rate sensitivity of 1.0. Anyhow, an effect of applied strain rates ranging from 0.1 – $0.8 s^{-1}$ on friction factors could not be found in experiments [GOE 91]. It is assumed that a dependency will arise when even higher strain rates are investigated due to overall increase of flow stress. At hot forming conditions, temperature effects should be taken into account. It is found that lubricants might be destroyed immediately at elevated temperatures or over the time when applied on hot dies [SCH 83]. Furthermore, the friction factors for some lubrication might show different kinds of temperature dependency [POS 98, PET 04]. In addition, the surface finish of dies might be important for some applications depending on the kind of lubrication used at hot conditions. Some graphite lubrications are found to break down on polished dies, while a surface roughness of about ~1 µm made the lubricant survive [SCH 83].

Thus, when analysing friction conditions in hot aluminium forging the following should be considered:

1) If a contact pressure dependency is assumed, friction tests should be performed at different die velocities. Flow stress of aluminium in hot forming is strongly dependent on strain rate. Thus, contact pressure at die-workpiece interface depends on die velocity. Alternatively, changes in the initial ring geometry might be useful to be able to vary the contact pressure conditions at die-workpiece interface [TAN 98].

2) If a dependency of the lubricant performance on sliding length is assumed or even a break down expected, friction tests should be performed at sliding lengths as those in the actual forming process, determined by experiments using the marker material technique [NOL 03b]. Surface extension of a workpiece, for example in forging, can vary considerably over time and area, and thus its distribution across a surface could be uneven for the same workpiece.

3) If temperature dependency of the lubricant performance is assumed, friction tests should be performed at the range of actual forging temperatures.

4) If ring compression tests are performed, calibration curves should be used obtained by FEM simulations to take different barrelling effects into account.

Ring compression can be performed for determination of friction factors to be used as input data in mathematical models. As alternatives to ring compression, pin-on-disc test, twin-disc test or the twist compression test may be used [HUN 95]. The task is to describe the interaction of the sliding workpiece material along die surfaces as exactly as possible. With changing friction the calculated results alter since the energy required for deformation increases with friction, as well as the inhomogeneity of deformation. This affects heat generation and thus flow behaviour of the deformed material. Further description of the ring compression test is given in chapter 2.3.6, page 35.

Usually, two definitions are used to express friction conditions: the so called *Coulomb friction* and the *shear friction* model. The first is based on *Amonton's laws*, where friction force F_f is proportional to normal load P and independent of the apparent area A. This combined with *Coulomb's law* which postulates that friction force is independent of sliding velocity the friction factor can be written as:

$$\mu = \frac{F_f}{P} = \frac{\tau_i}{p_i} \qquad (6)$$

where τ_i is the shear stress and p_i the pressure at die-workpiece interface (contact pressure). When τ_i reaches the value of k, which represents the yield stress of the workpiece material in pure shear, it will take less energy to shear inside the body of the workpiece while the surface remains immobile. Thus, the maximal friction coefficient equals $\mu = 0.577$ if the von Mises criterion is used (flow stress at pure shear $k = \sigma_f / \sqrt{3}$).

Another definition to describe friction is the law of constant friction stress, the so-called *Tresca friction law*:

$$\tau = mk = \frac{m \cdot \sigma_f}{\sqrt{3}} \text{ (using von Mises' flow criteria)} \qquad (7)$$

where m is the frictional shear factor. Usually m is considered to be constant over the entire surface and independent of the velocity. At $m \geq 1$ full sticking is represented and yield stress reached for the workpiece material in pure shear.

Both friction models are often used in analytical and numerical investigations of metal forming but do not take the sliding length and/or the temperature dependency into account. The friction factors have to be determined at the particular conditions, which arise during the actual process. These conditions have to be determined first. Because of complex forming processes, conditions might change during the course of deformation while the friction is often defined as constant over time and area and independent of sliding length.

Grid pattern method

Analytical models become more and more effective and precise, but there are difficulties encountered in arriving at an exact solution while analysing complex metal forming processes, especially non-steady state processes. Furthermore, mathematical models have to be verified by experimental investigations. Using experimental methods material flow can be observed either in actual, simplified and/or in a downscaled process. The forming process analysed might also be represented by special designed model materials while using adjusted conditions and often simplified processes. Such model materials are commonly waxes or mixtures of clay.

The analysis of deformation characteristics is very important because the properties and the quality of metal products are influenced by the manner in which the metal flows during the process to take up its final shape. By the study of the material flow, and how it is affected by changes in the conditions of operation of the process, a great deal of information can be obtained regarding the degree and distribution of local deformation. Results might also serve as input information for analytical models as e.g. when using slip line approaches.

Furthermore, information about local deformation is the key to assign the cause of forming defects like cracks, folding, un-filled die cavities, etc. Different experimental approaches have been developed to predict and to measure deformation characteristics. Experimental modelling techniques, along with *visioplasicity*, have been used for a very long time, were continuously improved [THO 65] and will be improved also in the future.

The technique used in this study is based on introducing local differences in composition of workpiece material using contrast metals. The difficult part of this technique is thus to make compositional changes so that they will not alter the original metal flow. The contrast metals used should all possess mechanical properties that are in close relation to those of the workpiece metal, or alternatively the amount of it should be small enough such that it cannot alter the metal flow. Local compositional changes can be achieved by inserting contrast metal or macro impurities. In general, different alloys with rather small differences in composition, i.e. difference with respect to just one alloying element, can make up a good contrast metal.

Use of indicator alloys for tracing of metal flow in metal forming was first introduced very early [UNC 28, FIE 39, BLA 48]. In the research environment at SINTEF and NTNU in Norway such techniques were taken into use quite early to study metal flow in hot extrusion processes. Work within this area was done by Lefstad and Valberg [LEF 87, LEF 92, VAL 84, VAL 88]. Later Lefstad elaborated this technique in quite fine detail to study outflow of outer surface layers of the billet material into extrusion [LEF 00]. Valberg and co-workers developed a special grid pattern technique where internal grid patterns were made by introduction of pins of indicator alloys into holes drilled into the workpiece [VAL 92]. In this way metal flow was studied with good accuracy in hot aluminium extrusion processes as forward extrusion [VAL 92a, VAL 92b], backward extrusion [VAL 92b], hollow profile extrusion [VAL 93b, WEL 95], two-hole extrusion [VAL 96a] and extrusion through long narrow channels [VAL 96b]. This work even resulted in a 3D-variant which was applied in direct extrusion of bars with square cross-section, and in extrusion of profiles with rectangular sections [VAL 93a], see Figure 8. The technique was further developed for application in cold forging processes as backwards cup-extrusion [VAL 00]. Finally, the technique was refined, and a method was developed to insert marker material in form of both stripes and tubes filled with workpiece material into workpieces [UYY 03, VAL 04, UYY 04]. The technique using marker material tubes resulted in the possibility of combining a surface grid made of rings with an internal grid made of lines. Uyyuru and Valberg [UYY 03, VAL 04] used this technique where marker material made of an aluminium alloy with a low content of copper was embedded in workpieces of another aluminium alloy without this constituent, see Figure 9. In this work metal flow in backward cup extrusion and plane strain compression was investigated in detail with high degree of accuracy.

Later, as part of this thesis work, Nolte and Valberg [NOL 03a, NOL 04a] analysed the surface straining history for different hot aluminium forging processes, using marker material tubes appearing as circular rings on the deformed surface of the workpiece, see Figure 9. Previously, deformed experimental grid patterns were also used for comparison with FEM simulations to study the material flow and to find friction regions by inverse modelling [NOL 03b, NOL 04c].

The grid pattern technique as described above using marker material resulting in both surface grids and internal grids is best suited for processes at which high strains arise as e.g. in forging, and especially in regions around the flash gap entrance, and in extrusion processes where high strains occur close to the bearing channel. Using an optical microscope, lines of contrast metal less than 0.1mm thickness may be detected [VAL 93a].

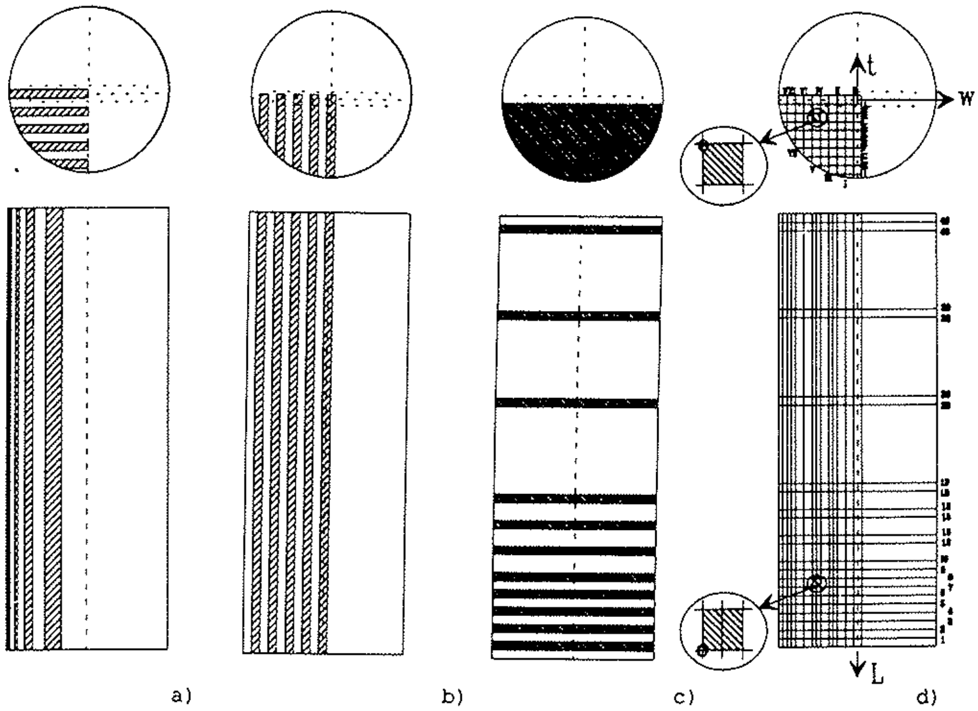


Figure 8. *Three-dimensional pattern obtained by inserting discs of indicator alloy into the billet [VAL 93a].*

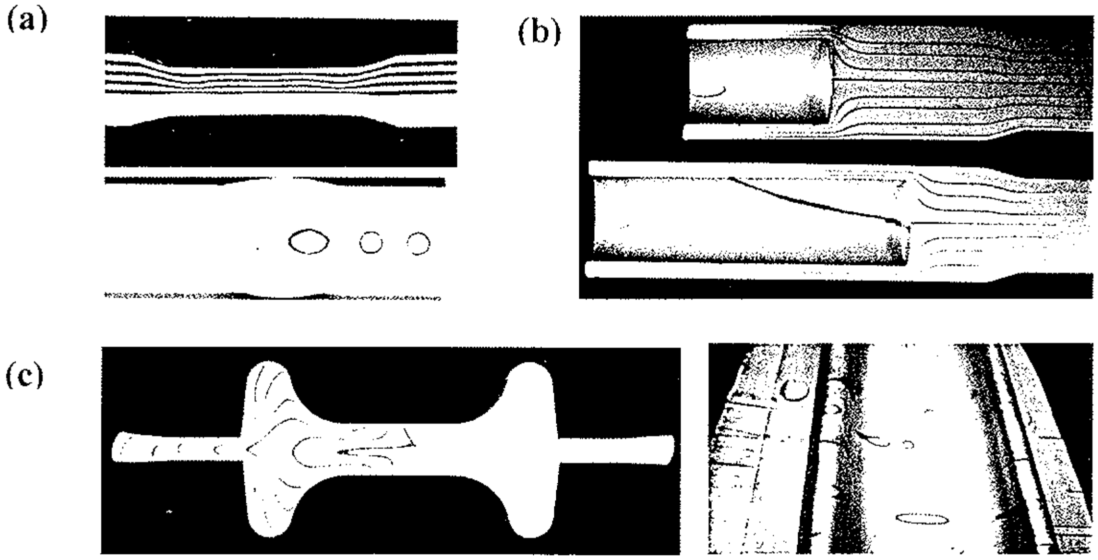


Figure 9. *(a) Grid pattern to investigate friction conditions in plane strain compression [UYY 03], (b) Grid pattern to investigate friction conditions in backward cup extrusion [UYY 03], (c) Internal grid and surface pattern used in hot forging of aluminium [NOL 03a, NOL 03b].*

Visioplasticity method

A method that combines experimental and mathematical analyses for determining stress and strain rates is called *visioplasticity*. It is a method by which the velocity vector field is established by experiment and the stresses are calculated therefrom [THO 65]. The accuracy of the results will depend on the quality of the experimental technique. Today, flow fields in sheet forming, or on surfaces, can be accomplished with very high resolution in ways of *printing methods*, *image correlation method* and *interferometrical methods*, which are further described in paper IV [NOL 04b]. To investigate material flow inside the workpiece, topographical changes on symmetry planes are commonly used for adding the required pattern used for analysis, having the disadvantage that resolution of the pattern might be lost at regions of high strains. By forging and extrusion of aluminium at hot and cold conditions an especially very high resolution may be achieved by the application of the *grid pattern technique* using marker material tubes, as mentioned above.

The advantage of the method lies in the fact that it will give stress, strain rate and strain distribution at any section for which the flow pattern has been obtained. Its disadvantage, of course, is that the experiment must be performed first, before any prediction can be made [THO 65].

1.4 Applied methods

1.4.1 Open-die forging analysis

Two different open-die hot forging processes were used to study material flow and interface conditions, namely (1) a ring compression test, and (2) a cylinder compression test. Variants of the alloys AA6082 and AA6060 were used in either cast or extruded condition. Results obtained from ring compression tests served as input data for friction modelling in simulations, as the results of the cylinder compression tests did so for flow stress modelling. The flow stress analysis was performed using a GLEEBLE^{TM} test machine at Hydro Aluminium, Sunndalsøra, Norway. To analyse the effect of grain orientation /anisotropy inside the forging stock, flow stress was determined in different directions inside an extruded rod. Cylinder compression tests to investigate the phenomena of double bulging were performed in NTNU's 60ton press and in SINTEF's 800ton press using an external load cell to record forging loads.

The *grid pattern technique* was used to obtain reliable information about workpiece sliding against die surfaces as well as surface expansion, which in turn can be used to evaluate the results of FE-simulations. In this way, the input friction data could be adjusted and friction factors determined by inverse modelling. The experimentally validated simulations were then used to analyse process conditions. The approach of analysis used is illustrated in Figure 10.

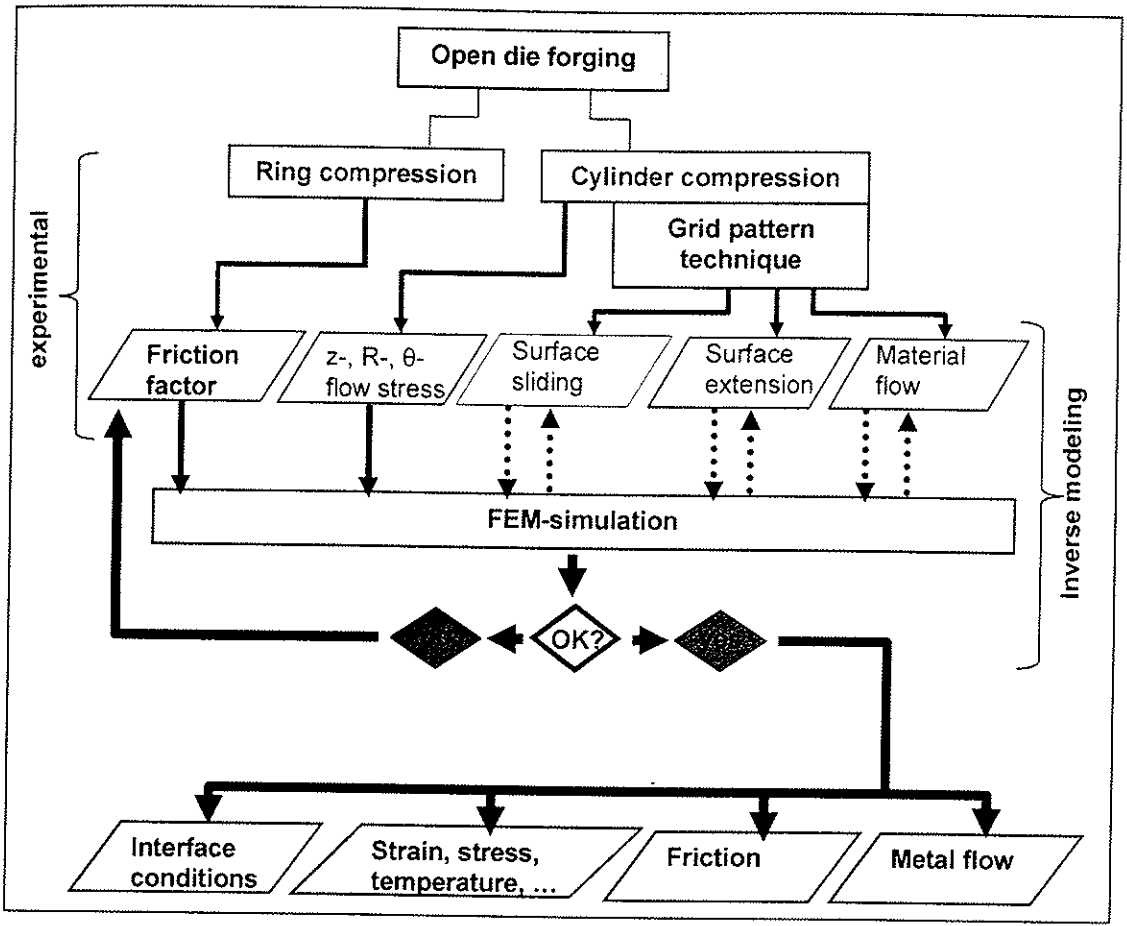


Figure 10. *Flow chart of the open-die forging processes combined with inverse modelling.*

1.4.2 Closed-die forging analysis

Two different dies were used to investigate the closed-die forging processes experimentally at conditions of hot forming: (1) a die to forge oblong parts with an H-shaped cross-section, and (2) a modular die made up of four tool pieces to forge axisymmetric parts, see Figure 7. The workpiece used to forge oblong parts was with and without internal grid pattern, but it was always forged in dies with a parallel flash land, see Figure 11a). The set up of simulations of the oblong forging was complicated by the position of the workpiece and the die mismatch as well as the inexact die geometry in experiments. With the help of the internal grid pattern and inverse modelling technique, friction regions and friction factors were found that would match experimental results in terms of material flow with high accuracy, cf. paper II [NOL 03b]. The workpiece applied in this die was always extruded rod orientated as in the industry, placed horizontally resting on the lower die.

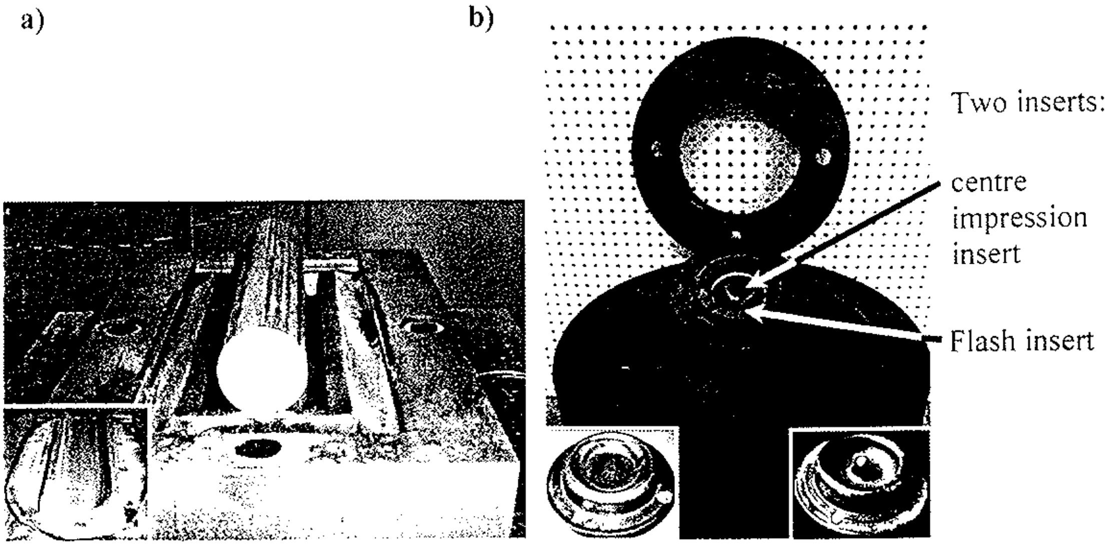


Figure 11. *a) Die to forge oblong parts with H-shaped cross-section and b) modular forging tool with exchangeable centre part and flash saddle to forge axisymmetric parts.*

The modular forging die was used to forge disc shaped parts with a peripheral rim and in addition with or without a hub in the centre, see Figure 11b). To obtain different shapes exchangeable die inserts were used with or without a centre cavity. Additionally, two different inserts representing the flash land were used, one with flat, parallel land and the other having same flash gap dimensions but a groove machined into the flash saddle, see Figure 7b) and paper VIII [NOL 04f]. The workpiece was always a cylinder, orientated either with its centre axis parallel or in direction perpendicular to the direction of forging. In one investigation, cylinders were machined from an extruded rod such that the centre axis of the cylinder became perpendicular to the extrusion direction of the rod. Hence, cylinders were either compressed along their vertical centre axis or, when lying horizontally on the lower die, on their sides, cf. paper VII [NOL 04e]. Investigations using internal grid patterns inside the workpiece in axisymmetric forging were performed for a specific forging geometry. The forging investigated this way was a disc shaped component with a peripheral rim forged in a die with parallel flash saddles. Surface extension and extension history was analysed for certain surface region by several samples forged to different partial forging steps, cf. paper III [NOL 04a].

Thus, the effect of orientation of initial workpiece, die geometry and die-workpiece interface conditions on material flow, strain, strain rate and temperature distributions could be investigated using finite element simulations which were proved to be reliable for our experimental conditions. The approach of analysis used is illustrated in Figure 12.

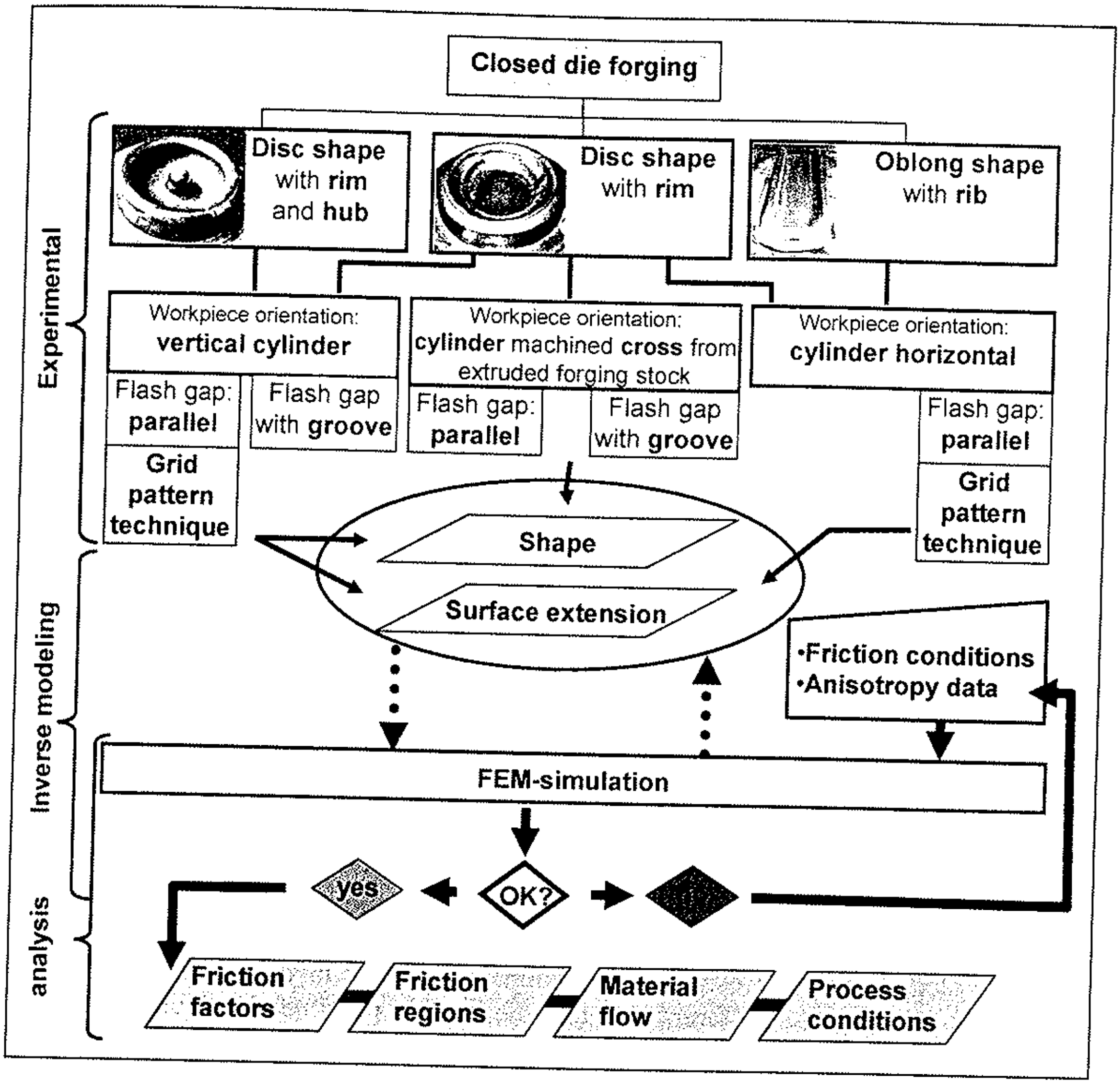


Figure 12. *Flow chart of the closed-die forging investigations performed with different die impressions and workpiece orientations.*

1.5 Objective of the study / Scope of the thesis

Until today, there is lack of precise experimental analysing methods to investigate material flow inside die cavity and along die-workpiece interfaces when forming materials by use of lubrication, as e.g. aluminium at conditions of hot forging, as in our case using oil-graphite lubrication. The task is to gain reliable information regarding surface straining with high resolution, using a technique which does not affect material flow itself, by changing lubrication or contact conditions. In addition, the information should maintain good resolution at high surface strains and/or contact pressures. At the same time, the technique should be easy to use.

There is still a need to improve mathematical models describing material flow behaviour and workpiece properties as e.g. anisotropy, and process conditions as friction. Today, optimised models and constitutive equations are implemented in numerical simulations. To evaluate the reliability of these models and the accuracy of constitutive equations, results of simulation and experiments are to compare. If a satisfactory validation of predictions is found, simulations may be used to investigate forging processes in detail with great accuracy.

This study covers experiments and finite element simulations of open-die and closed-die hot forging with flash formation using aluminium alloys. The aim was to gain a better understanding of metal flow, workpiece-tool interactions and the effect of certain process parameters in lubricated open-die as well as closed-die forging.

Open-die forging provides detailed information about friction conditions, material flow characteristics and anisotropy effects. Special designed and optimised grid pattern technique along with finite element simulations are used in investigations of open-die and closed-die forging. Different forging dies make possible the investigation of geometry effects on material flow of aluminium alloys. Here, the focus is on hot forging of the AA6082 alloy. Reliability of FE-simulations is evaluated using implemented mathematical models as an anisotropic material description and workpiece in different conditions.

The effects of following parameters was analysed in detail:

- friction conditions
- material anisotropy
- initial workpiece orientation
- die geometry

and the effect on resulting conditions described by means of:

- material flow
- surface strain
- die filling history
- stresses and strain inside die

An experimental measuring technique is described applicable in analysis to quantify surface strain as well as bulk material flow in hot forging. Material flow and surface straining is investigated using the grid pattern technique with marker material. Experimental results are compared with finite element simulations and an evaluation of the material flow predictions is done. So-called *inverse modelling* is used, in which results from repeated FE-simulations are compared with experimental results and a best choice of input parameters as e.g. friction parameters was extracted.

Numerical simulations are performed using the computer code DEFORM PC, DEFORM 2D and DEFORM 3D. New features like anisotropy are implemented from autumn 2003 and are used in the studies.

2 Summary of results

2.1 Abstracts of appended papers

Paper I:
Surface extension and material flow in hot aluminium forging investigated by use of FE-simulations and experiments

ABSTRACT. The computer code DEFORM is extensively used at NTNU in forging applications for investigation of die fill and analysis of defect formation. In addition, a special grid pattern technique using marker material has been developed. A forging tool has been set up which represents industrial hot forging of aluminium. The tool is used to study the variation of different forging parameters and their interaction on the forging result. The paper summarizes results of forging tests performed on the aluminium alloy AA6082, with forging conditions corresponding to those in industry. Material flow, die filling and surface extension were investigated with help of purpose made grid pattern. The results of the experiments are compared with 2-D computer simulations.

Paper II:
Material flow analysis in hot aluminium forging with special emphasis on the conditions in the flash gap

ABSTRACT. In hot aluminium forging it is often difficult to apply common surface strain analyzing techniques. A new experimental grid pattern technique was used successfully by us to determine surface strains over a section of a forging and to study material flow during forging operation in a laboratory hot forging process. This paper summarizes results of the forging tests performed on the aluminium alloy AA6082. Die filling and surface expansion were investigated along with the material flow inside the forging, and in the flash gap, with help of purpose made grid pattern, on the surface of, and inside the workpiece. The results of the experiments and the 2-D computer simulations, in which the forging process was reproduced, are presented and discussed.

Paper III:
Surface extension and material flow in axisymmetric hot aluminium forging

ABSTRACT. Until today, there is a high demand for an accurate and easy experimental method to prove the results of FE-simulations of complex aluminium hot forming. There is no easy and fast experimental technique available to investigate surface straining and material flow at the same time in lubricated hot aluminium forging. In recent years, a special grid pattern technique using marker material tubes has been developed at the Norwegian University of Science and Technology (NTNU) and tested in several applications such as plane strain compression and backward cup extrusion. After this, a forging tool having an industrial relevant impression was used to investigate surface extension and material flow in hot aluminium forging under plane strain conditions. An axisymmetric forging tool has finally, as reported here, been used to study the variation of different forging parameters in aluminium hot forging. This paper thus summarizes results of forging tests performed on the aluminium alloys AA6082 and AA 7108. The tests were performed under hot forging conditions corresponding to those used in industry. Material flow, die filling and surface extension were investigated by use of our newly modified grid pattern. It is concluded that the new grid pattern technique also has potential to be applicable in axisymmetric aluminium hot forging operations. The results of experiments are compared with 2-D computer simulations using the FEM-code DEFORM.

Paper IV:
Review and Recent Developments in Physical Modeling of Metal Forming

ABSTRACT. In order to acquire a better understanding of metal forming processes, different analytical and experimental approaches have been developed. Analytical models such as mathematical models are computational cost effective, but there are difficulties encountered in arriving at an exact solution while analyzing complex metal forming processes, especially non-steady state processes. Experimental modeling techniques, thus, have been used for a very long time, and were continuously improved until today as a complementary tool. In fact the error of analytical models as e.g. finite element simulations with appropriate data is generally inferior to the inaccuracies that are introduced by using special simulation materials (wax, different metals, etc.) in experimental technique. In general, experimental techniques are complementary to analytical models. A development guide on physical modeling of metal forming could be interest to the researchers in the field. However, a comprehensive review could not be found on the subject. In this article authors presented an historical review of development of physical modeling techniques in metal forming, while recent developments in the field are of importance in the article.

Paper V:
Traditional cylinder compression analyzed by help of internal stripe patterns

ABSTRACT. To study material flow of extruded aluminium alloy AA6082 under hot forging conditions cylinders of same diameter but different heights were compressed between heated parallel dies. The cylinders contained a special designed marker material pattern of vertical stripes inside a symmetry plane. After deformation the pattern were revealed and the exact positions of the marker material lines extending into the boundary interface between cylinder and die were measured. The stripe pattern as in initial state of cylinder was set up in simulations using the FEM-code DEFORM. Stripe patterns from simulations and experiments were compared at different stages of compression. The lubricant was a dry powder lubricant added to the dies by means of electro-static attraction. By manipulation of friction in simulation we tried to reproduce the experimental metal flow of the stripe pattern over the die-workpiece interface. In this way, i.e. by inverse modelling, for the lubricant applied in the experiments, we were able to deduce important information regarding friction, the main factor that controls metal flow over the die workpiece interface.

Paper VI:
Anisotropy effects in traditional aluminium cylinder compression

ABSTRACT. The phenomenon of double bulging, or formation of a twin barrel shape, was investigated in cylinder compression under conditions similar to hot forging of aluminium. Cylinders with initial aspect ratio of two, made from the alloys AA 6082 and AA 6060, in extruded and as-cast condition were compressed between heated parallel dies. After 25% reduction in height the extruded cylinder developed a double-bulge shape corresponding to earlier in literature reported shapes occurring in cold forming. When a cylinder of the same alloy in the as-cast condition was compressed the same way a single bulge formed. FE-simulations using an isotropic material description did not predict double bulging for these cylinders unless exaggerated external heat transfer parameters were used. Material flow characteristics and material state effects on the phenomenon of double bulging are discussed. Hills anisotropic material description was used to investigate the effect of anisotropy on metal flow in finite element simulations. When sufficient anisotropy was defined for the workpiece material the double bulging phenomenon did also appear in the simulation model.

Paper VII:
Effect of workpiece anisotropy on metal flow and forging conditions in hot aluminium forging

ABSTRACT. The workpiece in hot closed-die forging of aluminium is often taken from extruded forging stock which is known for strong crystallographic texture and thus anisotropic material properties. Anisotropy effects material flow and might lead to undesired shape of workpiece in the early stages of open-die forging of the process. Properties of the forging are also influenced by the orientation of the crystallographic texture in relation to direction of forging. In this investigation both experiments and finite element simulations are used to study how material flow depends on grain orientation inside the workpiece. In a laboratory hot forging process the effect of anisotropy on metal flow and forging conditions is investigated for three different aluminium alloys. Direction of forging is altered in comparison to orientation of the centre axis of the cylindrical workpiece applied. In addition, the effect of two different grain orientations inside initial workpiece is studied. Experiments are compared to simulations performed with the FEM-code DEFORM 3D v.502, in which the Hill's anisotropic material description is implemented. Good accordance between experiment and simulation is obtained when the flow stress in the extrusion direction of the forging stock is assumed ~20% higher than in the two perpendicular directions. Comparison was made between shape of the partial forging and corresponding simulated shape in the early open-die forging stages of the process. The largest deviation of predicted dimension of forging was ~6% in one case, while average deviation only was ~1%. In two cases, however, distortions and orientation of grain structure inside final forging were predicted wrong in simulation. It is concluded that deformation of internal zones inside the forging characterized by heavy shear is not well predicted by DEFORM even when the implemented anisotropy model is used.

Paper VIII:
The effect of die geometry on forging conditions in axisymmetric hot aluminium forging – an example

ABSTRACT. Filling of the die impression in hot closed-die forging depends strongly on the geometry of the impression and the flash gap. During course of deformation it is important to control the distribution of material inside impression of the die before the flash starts to form, and in later stages to understand the flow restraining effect in the flash gap. The stage before the workpiece material reaches the side walls of the impression might be critical with respect to eventual cracking if a material with low ductility is forged. At later stages, die cavity filling is controlled by flash gap design. The present investigation deals with effects regarding changes in material flow of alloy AA6082 as a result of small changes in die geometry in centre of an axisymmetric die. Furthermore, effect of flash land design on stresses inside the impression is investigated. The early open-die forging stages, and the later closed-die stages of filling of the die impression, are analyzed for two different impression geometries in centre of the die, and four different flash land designs. Experiments and FEM-simulations using the code DEFORM™ 2D are performed. A die with a small cavity in centre resulted in ~14% lower hoop stress during early forging before flash is formed, compared to a corresponding die without such a centre cavity. ~4% lower die load is predicted at the stroke length at which the cavity forming the rim of the forging is filled. Flash gap design characterised by decreasing the height of the flash gap resulted in reduced volume of flash, but also in ~14% higher radial stress at centre of the forging, compared to original design. A tapered flash gap with same volume reduction showed ~8% increase in radial stress. A parallel flash gap with grooves in the flash land, caused a higher volume of flash, and increased radial stress at the centre of the forging of ~7%. The effect of grooves on impression filling, by increased flow restriction is mainly dependent on width of grooves, and shear behaviour of workpiece material.

2.2 Results for open-die forging

2.2.1 Notation

In continuation, papers introduced in chapter 1.6, and presented in chapter 4, are numbered I-VIII according to treatment in chapter 1.6. Figures are cited in continuation by using figure number from actual paper followed by paper number, e.g. Figure 7 in paper V is denoted Figure 7-V.

Two open-die forging processes are used in investigations as described in more detail in chapter 1.4:

(1) Cylinder compression between flat, parallel dies
(2) Compression of cylinders between dies used in a axisymmetric closed-die forging process, Figure 11b)

In process (1), the *initial aspect ratio* is used to describe the proportions of a cylinder before deformation: initial aspect ratio (IAR) = cylinder height/diameter. Process (2) is analysed at the open-die forging stages in the beginning of the process.

2.2.2 Friction over the workpiece-die interface

Conditions at workpiece-die interface of great importance in metal forming are heat transfer, heat generation and friction between die and workpiece. These conditions control material flow, strain rate distribution, sliding of workpiece material along die surfaces, etc. The die geometry, the choice of material and the lubrication used influences these conditions strongly.

Cylinders of same diameter but three different heights were used in experiments to obtain different aspect ratios of initial cylinder. When compressing the cylinders between flat, parallel dies, it was observed that the average sliding distance of marker material exit-points along the die interface during cylinder compression increases when the cylinder aspect ratio is reduced. Figure 7-V [NOL 04c] shows that at end of compression the marker material pins in the shortest cylinder (IAR = 0.5) have been displaced in average nearly four times further along the die interface than corresponding pins in the tallest cylinder (IAR = 2).

For the powder lubricant used (GW61), it was not possible to reproduce the experimental behaviour in simulation, with respect to sliding across the die/workpiece interface, for cylinders (IAR = 1) by specifying constant shear friction factors over the contact interfaces, see Figure 9-V [NOL 04c]. Asymmetric flow represented by different sliding lengths at the top and bottom end surfaces of a cylinder (IAR = 0.5) was realistically reproduced in simulation using different shear friction factor values. This can bee seen in the good accordance between experimental and simulated pattern, Figure 10-V [NOL 04c]. Even so exact match of all marker material exit points could not be obtained in one simulation. The reason for the mismatch might be that the friction values in simulations were assumed constant both during the course of compression, and across the complete contact area at each end of the cylinder.

In cylinder compression between parallel dies, the change in pressure field along the die-workpiece interface due to the decrease of the aspect ratio was assumed to influence the friction conditions, see Figure 11-V [NOL 04c]. This phenomenon, including the fact that sliding lengths increase with decreasing aspect ratio throughout the course of cylinder compression, might explain why a constant value of the friction factor can not describe the friction conditions in the experiments.

2.2.3 Effects of the workpiece anisotropy

Generally, in open-die forging processes, anisotropy of the initial workpiece might be utilised on purpose to shape forgings to desired geometry or to strengthen components by orientating grain structures in an optimum way. Use of the initial workpiece with a strong grain orientation might be one reason why FE-simulations assuming isotropic material predicted wrong process conditions and material flow in comparison to experimental conditions. In case of wrong FEM-predictions, problems may arise in a newly developed process chain based on simulations. Wrong conclusions on assumed process parameters might also lead to component failure after development or optimisation of a particular forging process.

According to literature, flow stress might differ up to 30% in different directions in a workpiece cut from a forging stock. For one kind of extrusions used in cylinder compression, produced at an extrusion ratio $R = 3.7$, average flow stress was found to be about 8% lower in transverse direction than that in extrusion direction. Flow stress in the core of the rod in extrusion direction was about 2% lower than correspondingly in the outer surface layer. In transverse direction nearly no difference was found between the flow stress values in the centre and in the outer surface layer, see paper VI [NOL 04d].

Cylinders cut from this extruded rod when compressed at small compressive strains of $\varepsilon = 0.3$, between parallel dies showed a double bulge shape, while cylinders machined from the corresponding material in as-cast and homogenised condition developed a single bulge. In all other experiments, cylinders having an initial aspect ratio of 2.0, machined from different extruded forging stock, showed a double bulge shape at this small compressive strain. All cylinders machined from cast and homogenized billets showed a single bulge shape after the same reduction. Double bulging was obtained in simulation when using Hill's anisotropy material description. Using planar anisotropy, a ~30% higher flow stress in extrusion than in perpendicular directions had to be specified to obtain double bulging in simulations.

The anisotropy increases with extrusion ratio. Double bulging was shown to be more pronounced in cylinders made from rods produced at high extrusion ratios. Thus, double bulging is more pronounced in cylinders made from rods with strong anisotropic material behaviour.

During investigation of process (2) in the open-die forging stages it was found that compression of workpiece with extrusion direction orientated perpendicular to the cylinder axis resulted in an elliptical cylinder shape. The initial forging stock used in these experiments was extruded at extrusion ratio $R = \sim 10$. In simulations, ~20% higher flow stress in extrusion than in cross directions resulted in accurate FEM-predictions of the elliptical shape. Maximum shape deviation of simulated outline compared with experiments was ~ 6% after 19mm die stroke. Except for this the average shape deviation was ~1%.

2.2.4 Effects of the die geometry

The shape of open-die forgings may be altered by small changes of die impression as shown in our investigations, by adding a centre cavity into the die forming a hub in the middle of the disc shaped forging, see paper VIII [NOL 04f]. Forging load and material flow was significantly changed because of this small change in die geometry. This principle can be used to modify the shape of a part, to obtain reduced forces and changed distribution of internal and external flash.

In our case, strain rate and stress distribution in the open-die forging stages of process (2) changed distinctly with presence of a cavity at die centre. Hoop stress at the periphery was in one case lowered by ~14% at stroke level just before the material touches the outer wall of peripheral cavity. Risk of crack initiation might also be reduced in this way in axisymmetric forgings, or at corners of oblong forgings.

2.3 Results for closed-die forging

2.3.1 Notation

Two types of closed-die forging processes are used in investigations as described in more detail in chapter 1.4:

(3) Closed die forging of oblong components, Figure 11a). This forging process is very close to forging in plane strain.
(4) Closed die forging of axisymmetric components, Figure 11b), i.e. continuation of process (2).

2.3.2 Inverse modelling of friction

A grid pattern technique was used to get detailed information about material flow and surface straining during the course of plane-strain and axisymmetric forging, processes (3) and (4). Using this information, surface regions over the cross-section of the forging subjected to high and low strains during the forging process were determined and compared to corresponding conditions in simulations. Thus, the friction conditions, using the shear friction model, were adjusted in simulations to correspond to experimental observations with respect to regions of different straining due to different friction. This was obtained by using different *friction windows* in which friction was set with different values. The final good accordance between experiments and simulation with regard to expansion of workpiece surface and even metal flow inside the forging, proved that the assumed friction distribution was in fact reliable.

The die-workpiece interface of the forging process was divided into three main friction regions both in forging of oblong and axisymmetric parts: (1) the region from the centre of the impression to the top of the peripheral cavity that forms the rim and (2) from the top of the peripheral cavity to the entrance to the flash gap, and finally (3) over the flash land, see paper II and III, [NOL 03b, NOL 04a].

The friction factors were equal to, or higher then those found in ring compression tests performed for same material with same surface finish, and at the same temperature and lubrication conditions. Numerical value of friction factor in ring compression was $m = 0.5$ and in forging $m = 0.5\text{-}0.9$.

Friction factors were determined by inverse modelling using friction factors defined as constant over time. Thus, the resulting friction factors are average values for changing conditions during the whole course of forging.

2.3.3 Surface strain distribution

The surface strain distribution obtained in simulation is analysed for oblong forgings in the plane-strain direction and for axisymmetric forgings in the radial direction, see paper I, II, III [NOL 03a, NOL 03b, NOL 04a]. With regard to definition of surface strain see equation 8.

In both cases, for the oblong and the axisymmetric components, a peak value of surface strain occurs at inner side of the rim/rib of the forging. Here, the true strain at the end of forging was determined to be $\varepsilon = \sim 2$ for the oblong forgings and $\varepsilon = \sim 1$ for the axisymmetric forgings.

Material at the top of the rim/rib as well as at the outer impression wall is not stretched or compressed significantly. The highest straining is found at the flash gap entrance where true strains at the final step reached values of $\varepsilon = \sim 6$. The major straining occurs here when material flows into the flash gap. It was shown that surface straining due to sliding along the surface inside the flash gap caused maximum straining of $\varepsilon = \sim 0.8$ in our forgings.

In the axisymmetric forging, the surface at the inner side of the rim was subjected to stretching followed by later compression during the course of deformation. Thus, it is obvious that surface strain analysis needs to be performed at different stages of deformation.

2.3.4 Effect of initial workpiece positioning

In forging processes the initial workpiece is often taken from extrusions characterised by a strong crystallographic texture. Since forgings are supposed to have the best properties, the grain orientation of the initial and final workpiece must be taken into account when developing and optimising forging processes. It was shown in axisymmetric forging that FE-simulations assuming isotropic material could predict wrong material flow and might lead to wrong conclusions about final texture development.

It is found in process (4) that in some cases using extruded workpiece in certain orientation, distortion of the grain structure in experiments is not in good accordance with simulated flow lines, see paper VII [NOL 04e]. Thus, shear zones were in some cases predicted wrong, i.e. they were less developed in simulations than in experiments, see Figure VII-10.

2.3.5 Effect of flash gap geometry

Flash gap geometry is shown to strongly affect the stress distribution and the stress history inside the impression in simulation of an axisymmetric forging. Different flash gap designs with changes in terms of reduced height of the gap, tapered saddles and saddles with grooves at both sides were used in simulation to demonstrate effect of these changes on die load history and radial stress history inside an axisymmetric impression, see paper VIII [NOL 04f].

At end of our axisymmetric forging process, changed flash gap design resulted in a reduced volume of flash of ~1% when height of the flash gap was reduced, but at the same time ~14% higher radial stress at the centre of the forging, compared to the original design. A tapered flash gap with same volume reduction showed ~8% increase in radial stress. A parallel flash gap, with grooves at both sides of the flash land, caused a higher volume of flash of ~1%, and an increased radial stress in the centre of the forging of ~7%.

With 22.5% excess amount of material in flash, Bühler and Vieregge [BÜH 70] in steel forging of axisymmetric parts predicted about ~40% higher maximum pressure on the flash land when using a flash land with a groove in one of the flash saddles compared to parallel flash saddles without grooves. In our simulations using the same amount of excess material, ~20% higher pressure was exerted on the flash land for similar flash gap design using grooves in each flash saddle. Thus, shear deformation of aluminium at our conditions resulted in higher flow restriction in simulations than evoked by workpiece material only sliding along the flash land.

Different positions of grooves in flash land do not result in different stress conditions inside the impression after complete groove filling. But stress distributions are different along the flash gap. A groove close to the flash gap entrance is best as it restricts the material flow as early as possible. Groove width and shear behaviour of the workpiece material filling the groove is decisive with regard to magnitude of flow restriction, not the groove depth. Thus, several shallow, not too wide grooves can cause stronger restriction at earlier stroke level than one deep groove.

But a groove in a flash saddle represents a local increase in flash gap height. An increase in pressure on the flash land, and thus increased flow restriction, is only possible if the friction stresses increases significantly inside the flash gap because of presence of the groove, and out-weights the opposite effect of increased local flash height.

2.3.6 Strain at surface in relation to contact pressure

Inverse modelling of friction conditions was done in hot forming of a complicated oblong forging. Here, the experimental behaviour along boundary interface between die and workpiece was first quantified by help of an internal grid pattern [NOL 03b], and comparison were made with simulations where this behaviour was reproduced. Friction was described by a shear friction model. In this way higher friction values were determined in forging than found earlier in ring compression, see chapter 2.3.2. Later it was found that the determined friction windows and friction values lead to good accordance between experiments and simulations also at axisymmetric forging conditions, see paper III, VII, VIII [NOL 04a, NOL 04e, NOL 04f].

To evaluate the usefulness of test results from ring compression, predicted contact pressure at die-workpiece interface and surface extension in the axisymmetric laboratory process are compared with same parameters in ring compression simulations. The simulations used to analyse the laboratory process were the same as those in earlier investigations [NOL 04a, NOL 04e]. In ring compression simulations the same thermal, heat transfer, and material parameters were used as in the simulations of the laboratory forging process. Die velocity in ring compression simulations was set to 20mm/s according to forging experiments performed in the laboratory. Temperature of die was set to 450°C and workpiece temperature to 520°C according to earlier simulations. In the ring compression simulations, interface friction was modelled as shear friction with $m = 0.5$ according to the highest friction factor found in an investigation of the used oil-based lubricant at 520°C [MJØ 04]. The friction factor was defined as constant over time during forging and across the surface area.

True strain at the workpiece surface was calculated with the help of tracking of material points on the surface of the workpiece that moves in axial and/or radial direction during the forging process. Always two points are used to calculate the surface strain, in the following denoted as a *pair of points*. At different simulation steps the distances between points ($l_{1,2}$) were measured and divided by initial distance ($l_{1,2,0}$) to obtain surface strain:

$$\varepsilon = \ln(l_{1,2}/l_{1,2,0}) \tag{8}$$

The position of a pair of points at initial and analysed stage is illustrated in Figure 13. In axisymmetric forging the resulting strain value quantifies the degree of surface expansion in the radial direction but does not include expansion in the circumferential direction. In other investigations performed using the die to forge oblong components by nearly plane strain material flow, the strain value calculated this way represented total surface strain, see paper I and II [NOL 03a, NOL 03b].

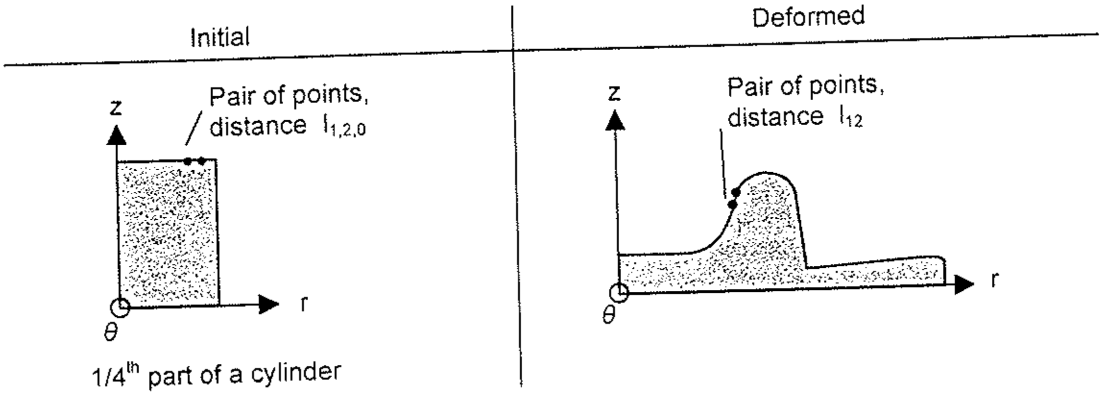


Figure 13. *Material points used to calculate surface strain in axisymmetric simulation.*

In the following figures calculated true strain in radial direction is presented for certain surface regions denoted by pairs points nos. 1 to 27. Contact pressure at die-workpiece interface can be plotted as state variable in DEFORM 2D v.8.02 and is extracted at various steps. Results taken this way from simulated laboratory processes are shown Figure 14 and Figure 15. All graphs are scaled to the same values of strain and contact pressure. Results for simulation of ring compression tests are shown in Figure 16.

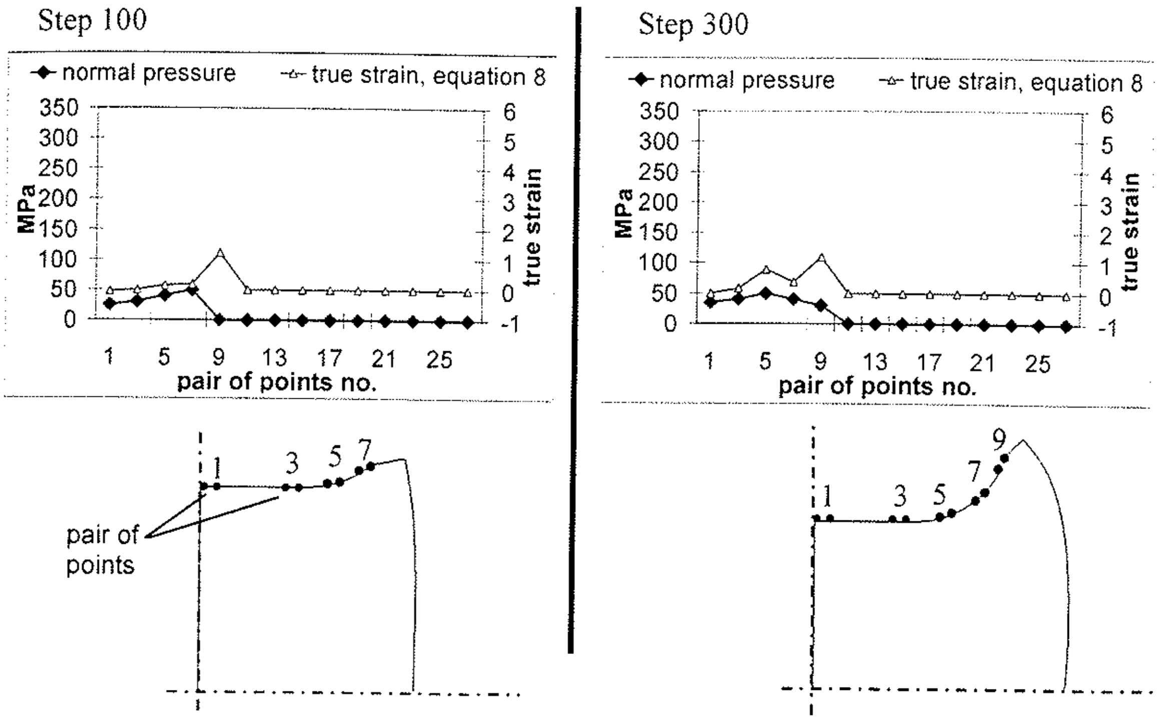


Figure 14. *Calculated contact pressure and true surface strain distribution of workpiece at different surface regions in radial direction at simulation steps no.100 and no.300 in the axisymmetric laboratory forging process.*

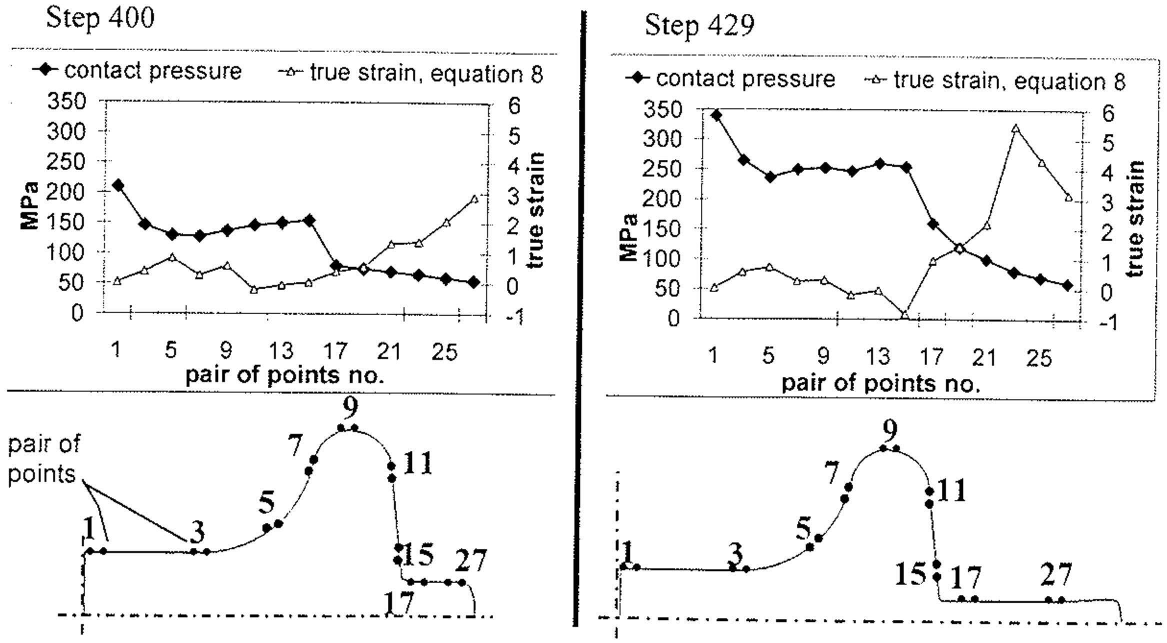


Figure 15. *Calculated contact pressure and true surface strain distribution of workpiece at different surface regions in radial direction at simulation steps no.400 and no.429 (final) in the axisymmetric laboratory forging process.*

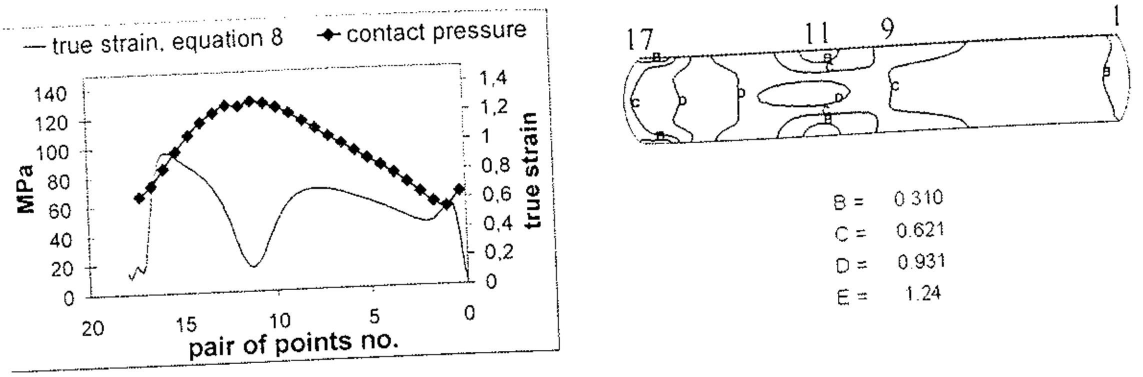


Figure 16. *Calculated contact pressure and true surface strain distribution in radial direction over the ring surface at 50% height reduction of ring used in friction test. Friction value set to m=0.5.*

During early stages of deformation a typical contact pressure distribution can be seen as known for cylinder compression having high aspect ratio (aspect ratio $AR = h/d =$ *height/diameter*), see step no.100 in Figure 14. The highest contact pressure value is at the periphery of the contact zone at the top of the sample. Also the surface strain shows maximum value at this location at the periphery of the contact zone. In the further course of deformation the contact pressure distribution begins to change, see step no.300. Contact pressure decreases from inner side of cavity (pair of points no.5) to the mid-region (pair of points no.1) of interface contact. However, when the cavity is filled, the highest contact pressure value is at the centre of the die, see step no.400 and step no.429 in Figure 15. The contact pressure decreases outwards from this region to a region at the inner side of the peripheral die cavity, where the pair of points no.5 is located at the instant when the die cavity fills, see Figure 15. From these points and outwards over the die impression the contact pressure curve shows a slight increase towards the entrance to the flash gap. Contact pressure along the flash land at end of forging is significant lower than that inside the impression and decreases slightly, approximately linearly, from the inlet to the exit of the flash gap. Figure 14 and Figure 15 show that the high contact pressure region in the middle of the die impression is characterised by rather low surface strains. On the other hand, inside the flash gap there are large surface strains but concurrently contact pressure is rather low.

The results as with respect to simulation of ring compression show a surface region at mid-breadth of the ring characterized by very low surface strains, Figure 16. From this neutral "plane" material at each side flows either towards the centre of the ring or outwards in the opposite direction. Exactly at the location where surface extension is lowest highest contact pressure values concurrently occur.

As mentioned earlier, to evaluate the applicability, or relevance of the test results from ring compression for our forging simulations, contact pressure and true surface strain are compared as predicted for these two processes. It is assumed that results are applicable if these conditions are approximately at the same level. As shown in Figure 14 and 15, the contact pressure and surface strain are varying over the surface of the forging and are different in level and distribution compared to the results from the ring compression tests, shown in Figure 16. In addition, the surface strain histories of different regions inside the die impression in forging vary significantly, also showing regions of extension followed by compression. Further analysis is done by comparing surface strain and contact pressure values for forging and ring compression directly in one graph, see Figure 17.

The surface region of the forging close to the centre of the impression, pair of points nos.1-9, Figure 17, do not experience surface strain above ~ 1 throughout the whole course of forging. After filling of the die cavity the contact pressure at die-workpiece interface increases during the course of deformation reaching highest level in centre of the impression. For pair of points nos.11-15, which first have established contact with the die wall in simulation step no.400, there is same increase in contact pressure as for pair of points nos.3-9, but for surface region denoted by latter points a surface contraction takes place later.

On the contrary, significant surface extension takes place when material flows into the flash gap. As known [NOL 04c], highest contact pressure in the flash gap arises at entrance to the gap while there is a decrease towards exit of the gap, see pair of points nos.17-27 in simulation step nos. 400 and 429. Strain values show a maximum at half the flash length, at pair of points no.23. The surface at pair of points no.27 does only extend very little during the last stages of forging because these points flow out early and leaves the flash gap.

Figure 18 shows the results of simulation of ring compression plotted along with the results presented in Figure 17. Surface straining in ring compression is roughly about the same level as in the centre of the forging, i.e. pair of points nos.1-15. Surface strains inside the flash gap in forging are considerably higher than those in ring compression. The contact pressure on the flash saddle is approximately on same level as in ring compression, but in the centre region of the forging there is much higher pressure than in ring compression. It is concluded that regions having relevant surface strain in ring compression do not have sufficient contact pressure and vice versa. Anyhow, in industry the process is stopped at stroke when complete filling is reached, here step no.400. At this stroke level the values of ring compression test are more relevant, i.e. they are not too far away from corresponding values in the forging process.

As described earlier, the friction values found by inverse modelling were higher at the region between pair of points nos.11-15 and nos.17-27, $m = 0.9$ and $m = 0.7$, respectively. These values were assumed constant over time in the simulations. In Figure 17 it is seen that the surface region between pair of points nos.17-27 is characterised by a strongly increasing strain but moderate increase in contact pressure. If one assumes that friction is depending on surface straining, the friction value inside the flash gap could change over time reaching a very high level at the final stroke. Thus, the value determined by inverse modelling is an average friction value defined as constant over time, which may not represent actual conditions. Further investigation of the significance of this phenomenon is necessary.

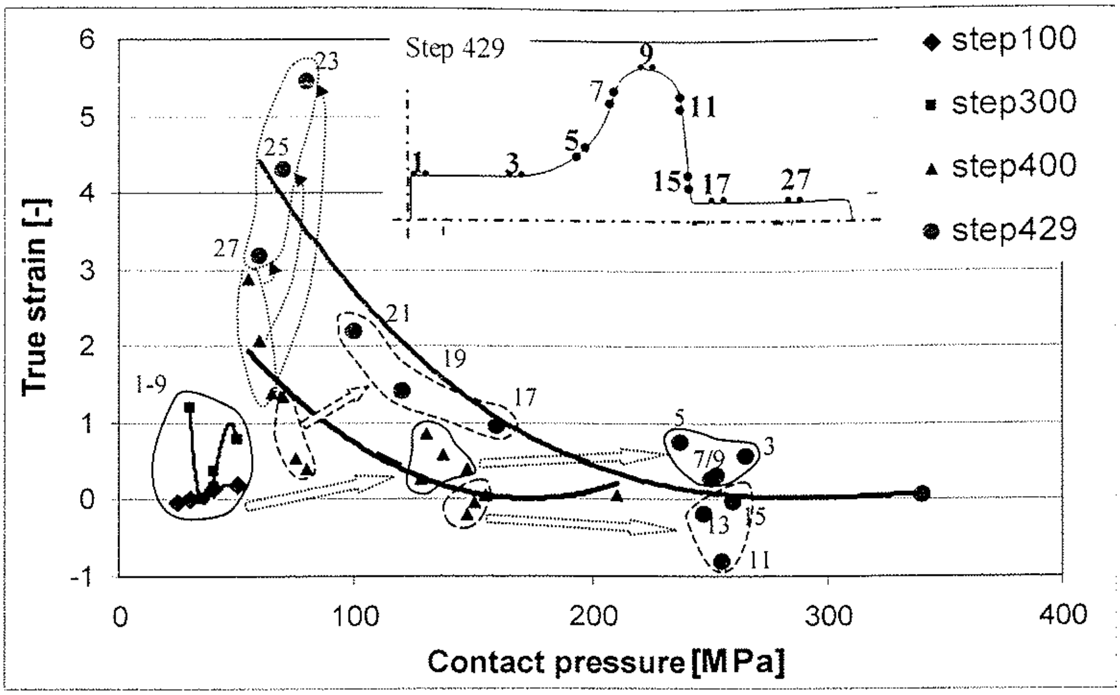


Figure 17. *Calculated contact pressure and true strain values over the workpiece surface. Numbers given are for pair of points shown for step no.429 in Figure 15 and Figure 16. Lines are trend lines at each step.*

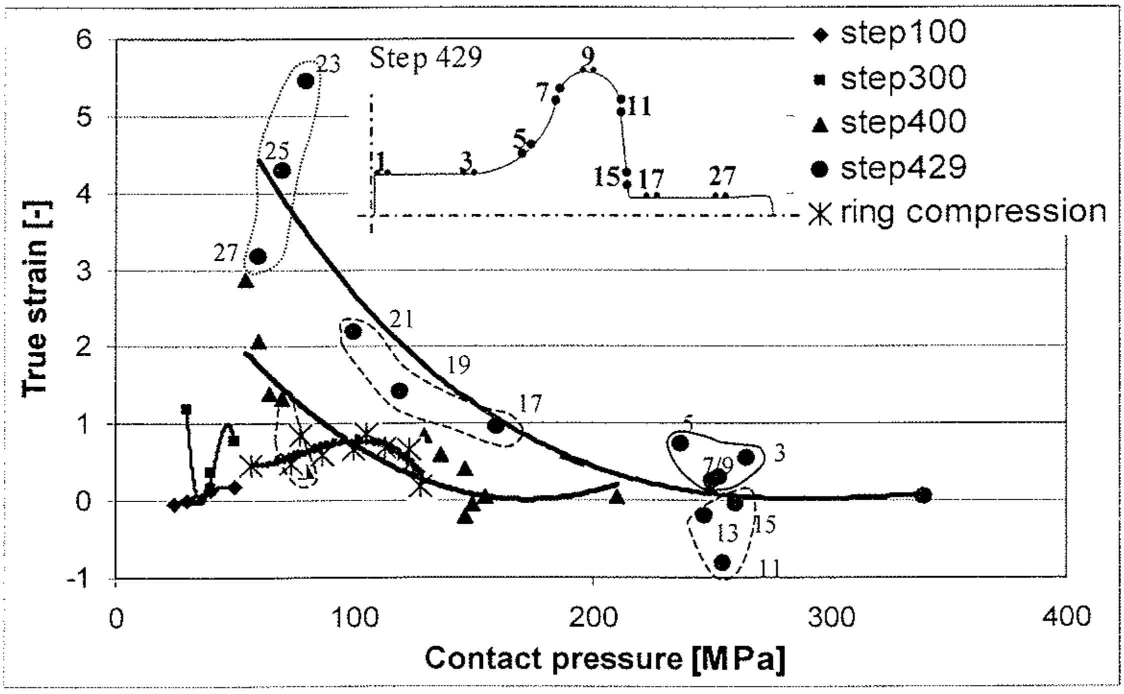


Figure 18. *Results of simulation of ring compression test compared to results of axisymmetric forging at different partial stages and end stage of forming.*

From the presented results the following conclusions can be drawn:

- Friction conditions seem to vary with contact pressure and surface strain.
- Surface strain in radial direction and contact pressure conditions vary within a broad range throughout the die stroke and also over the surface area of the die impression.
- Ring compression tests do not subject the workpiece surface to the same high surface strain values as those experienced at end of forging in the flash gap region of our particular forging process. Surface strain values of the axisymmetric forging are in reality up to 6 times higher than those in the ring compression tests.
- Ring compression tests do not reproduce the high contact pressure values appearing at the centre region of our axisymmetric forging. Contact pressure here at end of the forging process is twice that found in ring compression.
- For the given forging impression, friction values determined in ring compression will denote the lower bound of the friction factor.

3 Closing remarks

3.1 Conclusions

This thesis deals with analysis of the material flow and tool-workpiece interaction in hot forging. Efforts have been made to better understand the mechanics of hot forging processes using both numerical modelling and physical modelling techniques. Forging stock of extruded aluminium alloys were used as workpiece where from material data were determined and used in numerical modelling. In all FE-simulations the Tresca shear friction model was used to describe friction conditions.

Based on the investigations the following conclusions are drawn:

Workpiece

- In aluminium extrusions average flow stress is higher in the extrusion direction than in the transverse directions even at hot forming conditions. Using extruded forging stock, this might lead to undesired material flow in open die forging or in early stages of closed die forging processes, and could give component properties dependent on direction of loading. Further investigations and measurement of anisotropy is necessary to gain additional and more reliable data.

Open-die forging at hot forming conditions

- Friction conditions are not constant across the area of the die-workpiece interface when powder or mixtures of oil-graphite are used as lubrication.

- Cylinders with internal grid pattern can be used to determine sliding lengths and friction over the die-workpiece interface with good accuracy when compressed between flat parallel dies and dies of a closed die forging process.

- The material flow of a cylindrical workpiece in the open-die stages of a closed-die forging process is strongly dependent on both the extrusion ratio at which the forging stock is produced, and the orientation of the extrusion direction inside the workpiece.

- During compression of cylinders with a strong crystallographic texture orientated perpendicular to the direction of compression, i.e. in the radial direction of the cylinder, asymmetric shapes will develop.

- In compression of tall and slender cylinders using extruded workpiece material a double bulge shape occurs at small compressive strains when direction of compression and direction of extrusion coincides. When cast cylinders are compressed the same way there is no double bulging found.

- Using Hill's anisotropic flow criteria in simulation, stronger anisotropy is to assume than in experiments, to predict the corresponding double bulging behaviour.

- Using Hill's anisotropic flow criteria in simulations, asymmetric material flow is predicted with high accuracy by using parameters found by inverse modelling. In so doing, metal flow of cylinders having strong crystallographic texture orientated perpendicular to the direction of compression can be well predicted in simulations.

- Compression of cylinders machined from extrusions can eventually be developed into a test method to quantify anisotropy of forging stock. Before this is realised, geometry changes have to be related to the magnitude of anisotropy by aid of FE-simulations or theory.

- Risk of crack initiation can be reduced in axisymmetric forging by small intentional changes of die geometry, for instance by use of a small cavity at the centre of the die. A cavity at centre of the die give lower level of tensile hoop stresses during open-die forging stages of a closed-die forging process.

- The applicability of friction data obtained by ring compression tests in other forming processes can be evaluated by comparison of sliding lengths and contact pressure conditions in the test in relation to corresponding conditions in the actual forming process.

Closed-die forging at hot forming conditions

- The experimental grid pattern technique offered readable patterns at the surface of workpieces and inside them even at high strain and high contact pressure even though lubricants were used.

- Use of inverse modelling to determine friction models and numerical value of friction factor, and its distribution over the die impression, was possible by help of the grid pattern technique.

- Friction values found by inverse modelling in closed-die forging processes were always equal to or higher than those found in ring compression tests.

- Three regions inside the die impressions were found which had different friction conditions, both for our oblong parts and for the axisymmetric forgings, i.e. the region (1) from the vertical centre of forging to the top of the rim, (2) from the top of the rim to the flash gap entrance and (3) inside the flash land.

- In closed-die forging of oblong and axisymmetric parts there was a region of maximum surface strain located at the inner side of the rim or rib of the forging.
- The largest surface straining of the workpiece was at the flash gap entrance. Here, the major straining occurs when material flows into the flash gap. Inside the flash gap itself there is less straining.
- Analyses of grain distortions inside the side-pressed workpiece showed that flow behaviour in terms of shear band formation inside the extruded alloy AA6082 was not simulated correctly using Hill's or von Mises' flow criteria.
- Grain orientation inside initial workpiece must be taken into account when developing and optimising forged components, or forging processes. This is necessary to predict material flow correctly by simulations, and also final component properties which depend on grain structure.
- Flash gap design was shown to have influence on the distribution of pressure, and its time history, inside the die impressions. The parallel flash gap design seems to be the best choice, grooves in flash saddles or a tapered flash gap might be used to increase flow restriction in the gap.
- Small changes of the impression geometry, i.e. use of a small centre cavity, can be used to control material flow history and thus, improve cavity filling.

3.2 Recommended future work

Based on the investigations and conclusions made, the following tasks are recommended for future studies:

- Further investigation of anisotropy effects in hot forming is necessary to gain reliable anisotropy data of workpiece material.
- Flow behaviour of the alloy AA6082 should be studied when subjected to high shear strains in hot conditions. Under these conditions different flow criteria should also be evaluated and optimised to describe real behaviour of metal.
- In addition to the von Mises' and the Hill's flow criteria, alternative flow criteria should be tested in FE-simulations.
- Friction formulated as function of sliding length and contact pressure should be implemented in FE-simulations and evaluated by comparison to experiments.

- Bonding of marker material and matrix material should be improved for use of grid pattern technique during forming conditions characterised by tensile stress.

- New techniques to form grids on surfaces should be tested: for instance a grid applied by laser welding of a sheet of marker material on test sample [NOL 04g]. See Figure 19 for introductory results.

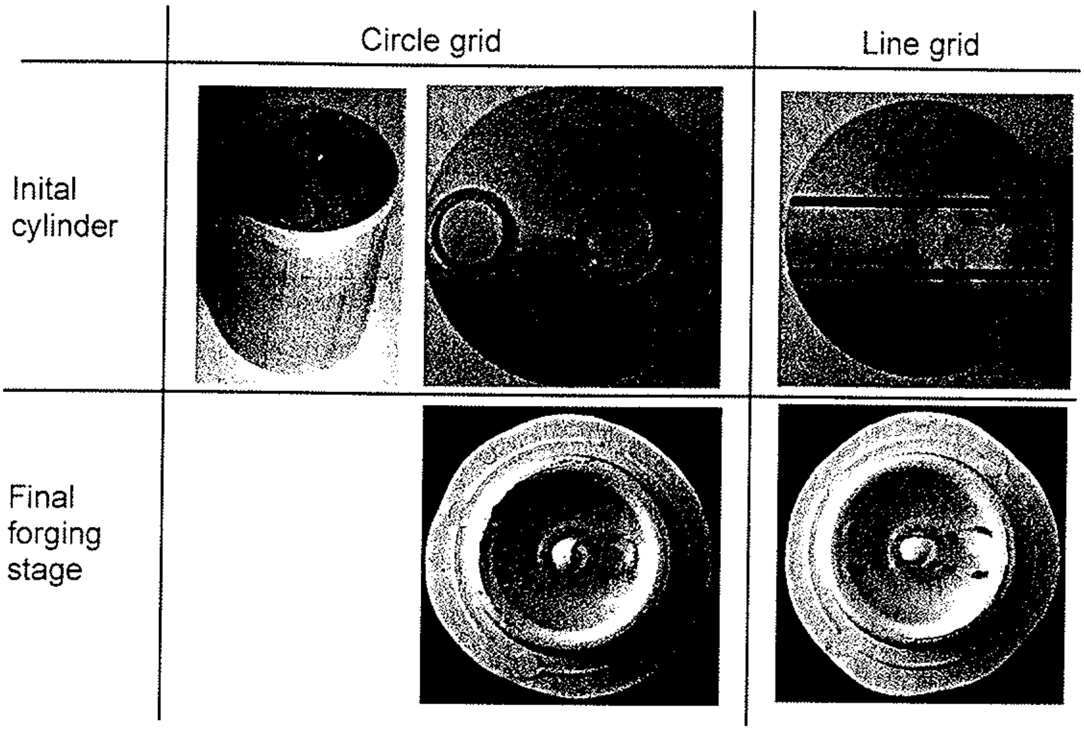


Figure 19. *Surface grid made by laser welding of marker material sheets onto test samples. The laser is positioning the grid by an accuracy of 0.1mm [NOL 04g].*

Bibliography

[ALT 86] T. Altan, S. Oh, H. Gegel: Metal Forming, Fundamentals and Applications, ASM, Metals Park, Ohio, 1986, pp. 1-3, 131-141, 144.

[AVI 69] B. Avitzur: Bulge in Hollow Disc Forging, Tech. Rep. AFMLTR-69-261, November 1969 (U.S. Air Force Materials Laboratory, Wright-Patterson Air Force Base, OH); NTIS Tech. Rep. 864 883, National Technical Information Service, 1969.

[BAN 03] D. Banabica, T. Kuwabarac, T. Baland, D.S. Comsaa, D. Juleana: Non-quadratic yield criterion for orthotropic sheet metals under plane-stress conditions, Int. J. Mech. Sci., vol. 45, 2003, pp. 797–811.

[BAR 89] F. Barlat, J. Lian: Plastic Behaviour and Stretchability of Sheer Metals. Part-I: A Yield Function for Orthotropic Sheets und Plane Stress Conditions, Int. J. Plasticity, vol. 5, 1989, pp. 51-66.

[BAR 91] F. Barlat, D.J. Lege, J.C. Brem: A six-component yield function for anisotropic materials, Int. J. Plasticity, vol. 7, 1991, pp. 693–712.

[BAR 97] F. Barlat, et al: Yield Function Development for Aluminium Alloy Sheets, J. Mech. Phys. Solids, vol. 45, 1997, pp. 1727-1763.

[BLA 48] C. Blazey, L. Broad, W.S. Gummer, D.B. Thompson: The Flow of Metal in Tube Extrusion, The journal of the Institute of Metals, vol. 75, 1948-1949, pp. 163-184.

[BIS 58] J.F. Bishop: On the Effect of Friction on Compression and Indentation Between Flat Dies, J. Mech. Phys. Solids, vol. 6, 1958, pp.132-144.

[BOD 03] J. Bodin: Sänksmide, IVF Industrifroskning och utveckling AB, Mölndal, Sweden, 2003 (in Swedish).

[BUG 93] A. Bugini, G. Maccarini, C. Giardini: The evaluation of Flow Stress and Friction in Upsetting of Rings and Cylinders, Annals of the CIRP, vol. 42-1, 1993, pp. 335-338.

[BRO 04] F. Bron, J. Besson: A yield function for anisotropic materials Application to aluminium alloys, Int. J. Plasticity, vol. 20, 2004, pp. 937-963.

[COU 43] R. Courant: Variational Methods For The Solution of Problems of Equilibrium and Vibrations, Bulletin of the American Mathematical Society, vol. 49, 1942.

[DES 72] C.S. Desai, J.F. Abel: Introduction to the finite element method, van Nostrand-Reinhold Co., New York, 1972.

[ETT 84] O.M. Ettouney, K.A. Stelson: A Modified Slab Method for Axisymmetric Upset Forging, 12th NAMRC, SME, 1984, pp. 133-140.

[FIE 39] R. Fiedler: Technologie des Pressens (The technology of forging), Magnesium und seine Legierungen, Springer, Berlin, 1939, pp. 374-382 (in German).

[GOE 91] R.L. Goetz, V.K. Jain, J.T. Morgan, M.W. Wierschke: Effects of material and processing conditions upon ring calibration curves, Wear, vol. 143, 1997, pp. 71-86.

[GRE 55] A.P. Green: On the unsymmetrical Extrusion in Plane Strain, J. Mech. Phys. Solids, vol. 3, 1955, pp. 189-196.

[GÜN 90] S. Güngör, L. Edwards: Effect of surface texture on small fatigue crack growth in a forged 6082 aluminium alloy, Fatigue 90, vol. 2, July 1990, p. 1073 – 1078.

[GÜN 93] S. Güngör, L. Edwards: Effect of surface texture on the initiation and propagation of small fatigue cracks in a forged 6082 aluminium alloy, Journal of Material Science and Engineering, A 160, 1993, p. 17 – 24.

[HAN 02] H. Han: Influence of Material Anisotropy and Friction on Ring Deformation, Journal of Tribology, vol. 124, 2002, pp. 637-644.

[HEN 23] H. Hencky: Über einige statisch bestimmte Fälle des Gleichgewichts in plastischen Körpern, Z. Angew. Math. Mech., vol. 3, 1923, pp. 241-251 (in German).

[HIL 50] R. Hill: The Mathematical Theory of Plasticity, Oxford at the Clarendon Press, 1950.

[HIL 90] R. Hill: Constitutive Modelling of Orthotropic Plasticity in Sheet metals, J. Mech. Phys. Solids, vol. 38, no3, 1990, pp. 405-417.

[HOS 93] W.F. Hosford, R.M. Caddell: Metal Forming, Mechanics and metallurgy, PTR Prentice Hall, New York, 1993, pp. 270-280.

[HUN 95] J. Hunding: Friction and Lubrication in Cold Forging, M.Sc. Thesis, publication number: MM95.07, Inst. of Manufacturing Engineering, Tech. Univ. of Denmark, 1995, pp. 19-30, 103-115.

[IVE 00] T. Iveland: Anisotropic plasticity of AlZnMg extrusions – an experimental approach, Norwegian University of Science and Technology, PhD thesis, IME report no.: 2000:18, 2000.

[JEN 03] O. Jensrud, R. Østhus, H. Langeng: New Development of Aluminium Forging and use of Physical and Numerical Process Simulation, Proc. of the 6th International ESAFORM Conference on Material Forming, Sorrento, Italy, 2003, pp. 959-962.

[KAR 25] Th. Von Karmann: Contribution to the Theory of Rolling, Z. angew. Math. Mech., vol. 5, 1925, pp. 139 – 141 (in German).

[KAR 93] A.P. Karafillis, M.C. Boyce: A General Anisotropic Yield Criterion using Bounds and a Transformation Weighting Tensor, J. Mech. Phys. Solids, vol. 41, no. 12, 1993, pp. 1859-1886.

[KAL 84] S. Kalpakjian: Manufacturing processes for Engineering Materials, Addison-Wesley Publishing Company, Reading, Massachusetts, 1984, pp. 289-298.

[KOB 89] S. Kobayashi, S.-I. Oh, T. Altan: Metal Forming and The Finite-Element Method, Oxford University Press, 1989, p. 1-2,

[KOV 96] E. Kovacs-Csetenyi, N.Q. Chih, I. Kovacs: Effect of microstructure on the hot deformation characteristics of aluminium alloys, Materials Science Forum, Vols. 217 – 222, 1996, p. 1775 – 1180.

[KUN 54] M. Kunogi: Reports of the scientific research Institute, vol. 30, Tokyo, 1954, p 63.

[KWA 02] C.T. Kwan: An analysis of the closed-die forging of a general axi-symmetric shape by the upper-bound elemental technique, J. Mat. Proc. Tech., vol. 123, 2002, pp. 197-202.

[LAD 99a] O.-G. Lademo, O.S. Hopperstad, M. Langseth: An evaluation of yield criteria and flow rules for aluminium alloys, International Journal of Plasticity, vol. 15, 1999, pp. 191-208.

[LAD 99b] O.-G. Lademo: Engineering Models of Elastoplasticity and Fracture for Aluminium Alloys, Norwegian University of Science and Technology, PdD thesis, no. 1999:39, 1999.

[LAD 02] O.-G. Lademo, O.S. Hopperstad, K.A. Malo, K.O. Pedersen: Modelling of plastic anisotropy in heat-treated aluminium extrusions, Journal of Materials Processing Technology, vol. 125–126, 2002, pp. 84–88.

[LAD 04] O.-G. Lademo, T.Berstad, O.S. Hopperstad, K.O. Pedersen: A numerical tool for formability analysis of aluminium alloys. Part I: Theory, Steel Grips, vol. 2, Suppl. Metal Forming, 2004, pp. 427-431.

[LAN 85] K. Lange: Handbook of metal forming, McGraw-Hill Book Company, New York, 1985, pp. 2.1-2.22, 11.5-11.6.

[LEE 52] E.H. Lee: The theoretical Analysis of Metal Forming Problems in Plain Strain, J. Appl. Mech., vol. 19, 1952, pp. 97-103.

[LEE 72] C.H. Lee, T. Altan: Influence of Flow Stress and Friction upon Metal flow in Upset Forging of Rings and Cylinders, Transaction ASME, Journal of Eng. for Industry, vol. 94, pp. 775-782.

[LEF 87] M. Lefstad: Flow of the Billet Surface in Extrusion, STF16 A87060, presented at 8th International Light Metals Congress, Leoben – Vienna, 1987, pp. 312 - 315.

[LEF 92] M. Lefstad , O. Reiso, V. Johnsen: Flow of the Billet Surface in Aluminium Extrusion, Proc. 5th Int. Al. Extr. Techn. Sem., Chicago, Vol.1, 1992, pp. 503-517.

[LEF 00] M. Lefstad, O. Reiso, V. Johnsen, S. Rystad: Billet Surface flow in Aluminium Extrusion, STF24 S20701, presented at the 4th World congress, Aluminium 2000, Montichiari (Brescia), Italy, 2000.

[LIS 04] C.J. Lissenden, J. F. Colaiuta: Hardening behavior of three metallic alloys under combined stresses at elevated temperature, Acta Mechanica, vol. 169, 2004, pp. 53–77.

[MIE 91] E.M. Mielnik: Metalworking Science and Engineering, McGraw Hill Inc., New York, 1991, pp. 174-181, 219-328, 477-482, 566-591.

[MIS 13] R. von Mises: Mechanik der festen Körper im plastisch deformablen Zustand, Göttinger Nachrichten, math.-phys. Kl., 1913, pp. 582-592.

[MJØ 04] H. Mjøen: Investigation of the friction coefficient for different lubricants used in hot forging of aluminium, Proceedings of a forging seminar at NTNU/SINTEF, Trondheim, Norway, 2004, internal paper.

[NOL 03a] D. Nolte, H. Valberg: Surface extension and material flow in hot aluminium forging investigated by use of FE-simulations and experiments, 6th International ESAFORM Conference on Material Forming, Sorrento, Italy, 2003, pp. 947-950.

[NOL 03b] D. Nolte, H. Valberg: Material Flow Analysis in Hot Aluminium Forging with Special Emphasis on the Conditions in the Flash Gap, Proceedings of the Int. Conf.: New Developments in Forging Technology, Stuttgart, Germany, 2003, pp. 389-409.

[NOL 04a] D. Nolte, H. Valberg: Surface extension and material flow in axisymmetric hot aluminium forging, Proc. of the 7th ESAFORM Conf., Trondheim, Norway, 2004, pp. 627-630.

[NOL 04b] D. Nolte, R. K. Uyyuru: Review and Recent Developments in Physical Modeling of Metal Forming, submitted to the International Journal of Forming Processes (IJFP), IJFP manuscript number: 222, paper accepted for publication.

[NOL 04c] D. Nolte, H. Valberg: Traditional Cylinder Compression Analyzed by Help of Internal Stripe Patterns, submitted to International Journal of Forming Processes (IJFP), July 2004.

[NOL 04d] D. Nolte, H. Valberg: Anisotropy effects in traditional cylinder compression of aluminium, submitted to International Journal of Forming Processes (IJFP), October 2004.

[NOL 04e] D. Nolte, H. Valberg: Effect of Workpiece Anisotropy on metal flow and forging conditions in Hot Aluminium Forging, submitted to International Journal of Forming Processes (IJFP), October 2004.

[NOL 04f] D. Nolte, H. Valberg: The Effect of Die Geometry on Forging Conditions in Axisymmetric Hot Aluminium Forging – an Example, submitted to International Journal of Forming Processes (IJFP), october 2004.

[NOL 04g] D. Nolte: Surface extension in axisymmetric hot aluminium forging analysed by help of grid pattern applied by laser welding, unpublished work, 2004.

[OXL 57] P.L.B. Oxley: A photographic investigation of the metal cutting Process, Ph.D. thesis for the University of Leeds, England, 1957.

[PET 04] P.A. Petrov, V.I. Perfilov, M.A. Petrov: Experimental and numerical investigation of friction in hot isothermal deformation of aluminium A92618, 7th ESAFORM Conference on Metal Forming, Trondheim, Norway, 2004, pp. 631-634.

[POS 98] B. Post-Pedersen, T. Wanheim, N. Bay: Verification of a friction test for warm and hot forging, IMechE, 1998, pp.253-261.

[PRA 23] L. Prandtl: Anwendungsbeispiele zu einem Henckyschen Satz über das Gleichgewicht, Z. Angew. Math. Mech., vol. 3, 1923, pp. 401-406.

[SIE 25] E. Siebel: Forces and Material Flow in Plastic Deformation, Stahl und Eisen, vol. 45, 1925, pp. 1563-1566 (in German).

[SCH 83] J.A. Schey: Tribology in Metal Working, American Society for Metals, Metals Park, Ohio, 1983, pp. 465-502

[STO 04] T. B. Stoughton: A non-associated flow rule for sheet metal forming, International Journal of Plasticity, vol. 18, 2002, pp. 687–714.

[STØ 03] S. Støren. P.T. Moe: Extrusion, in: G.E. Totten, D.S. MacKenzie: Handbook of Aluminum, vol.1, Marcel Dekker, Inc., New York-Basel, 2003, pp. 385-480.

[TAN 98] X. Tan, P.A.F. Martins, N. Bay, W. Zhang: Friction studies at different normal pressures with alternative ring compression test, Journal of Materials Processing Technology, vol. 80-81, 1998, pp. 292-297.

[THO 65] E.G. Thomsen, C.T. Yang, S. Kobayashi: Plastic deformation in metal processing, The Macmillan Company, New York, 1965, pp. 158-175.

[TRE 64] H. Tresca: Sur l'écoulement des corps solides soumis á de fortes pressions, Comptes Rendus, vol. 59, 1864, p. 754 and vol. 64, 1867, p. 809.

[UNC 28] H. Unckel: Einiges über die Fliessbewegung beim Pressen von Stangen und Rohren, sowie beim Ziehen (Some comments on material flow in full forward and tube extrusion as well as wire drawing), Zeitschrift für Metallkunde, vol. 20, no. 9, September 1928, pp. 323-330 (in German).

[UYY 03] R.K. Uyyuru: Engineering the friction and forming mechanics in cold aluminium forming - Use of modeling techniques, PhD thesis, no. 34, Norwegian University of Science and Technology, Trondheim, Norway, 2003.

[UYY 04] R.K. Uyyuru, H. Valberg: *Friction induced material flow in plane strain compression test*, Proceedings of the 2nd Int. Conf. on Tribology in Manuf. Proc., Nyborg, Denmark, Vol.2, 2004, pp. 465-474.

[VAL 84] H. Valberg, A.W. Hansen, and J.O. Loeland: Metal Flow at the Die in Aluminium Extrusion, Proc. 3rd Int'l Al. Extr. Techn. Sem., Atlanta, Vol.1, April 22-27, 1984, pp. 203-208.

[VAL 88] H. Valberg: Surface formation in Al-extrusion (Direct Extrusion), Proc. 4th. Int'l Al. Extr. Techn. Sem., Chicago, Vol.2, Apr. 11-14, 1988, pp. 309-320.

[VAL 92a] H. Valberg.: Metal Flow in the Direct Axisymmetric Extrusion of Aluminium, J. Mat. Proc. Techn., 31 (1992), pp. 39-55.

[VAL 92b] H. Valberg: Metal Flow in Direct, Indirect and Porthole Die Extrusion, Proc. 5th Int. Al. Extr. Techn. Sem., May 19-22, Chicago, Vol.1, 1992, pp. 337-357.

[VAL 93a] H. Valberg, A.W. Hansen. and R. Kovacs; Deformation in hot extrusion investigated by means of a 3-D Grid pattern Technique; Advanced Technology of Plasticity 1993 - Proceeding of the Fourth International Conference on Technology of Plasticity, Beijing, China. 1993, pp. 637-645.

[VAL 93b] H. Valberg, and R.A. Groenseth: Deformation and Metal Flow when Extruding Hollow Aluminium Profiles, Int. J. Mat. Prod. Techn., 8 (1993) 1, pp. 1-22.

[WEL 95] T. Welo, A. Smaabrekke and H. Valberg: Two-Dimensional Simulation of Porthole Extrusion. Aluminium, vol. 71, no. 1, 1995, pp. 90-94.

[VAL 96a] H. Valberg, F.P. Coenen and R. Kopp: Metal Flow in Two-Hole Extrusion, Proc. 6th Int. Al. Extr. Techn. Sem., May 14-17, Chicago, 1996, Vol.2, pp. 113-124.

[VAL 96b] H. Valberg and T. Malvik: Metal Flow in Die Channels of Extrusion, Proc. 6th Int. Al. Extr. Techn. Sem., May 14-17, Chicago, 1996, Vol.2, pp. 17-28.

[VAL 00] H. Valberg, K. Karlsen and H. Berg: Extension of the end-face of the slug over the punch in backwards impact extrusion of aluminium alloys, Int. J. of Materials & Product Technology, Vol.15, No.6, 2000, pp. 535-553.

[VAL 04] H. Valberg, R.K.Uyyuru: New accurate experimental techniques to quantify metal flow inside workpice – and along boundary interface of workpiece – in metal forming, Proceedings of the 2nd Int. Conf. on Tribology in Manuf. Proc., Nyborg, Denmark, Vol.2, 2004, pp. 453-474.

[ZEN 44] C. Zener, J.H. Hollomon: Effect of Strain Rate upon Plastic Flow of Steels, Journal of Appl. Phys., vol. 15, 1944, p. 22.

[ZHA 04] D. Zhao, S. Lampman: Hot Tension and Compression Testing - Effects of Temperature, ASM Materials Information, http://products.asminternational.org/matinfo/index.jsp, 2004.