XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

EXPERIMENTAL AND NUMERICAL ANALYSIS OF THE FLOW BEHAVIOUR OF MAGNESIUM WROUGHT ALLOY AZ31 FOR DEEP DRAWING PROCESSES AT ELEVATED TEMPERATURES

B.-A. BEHRENS*, A. BOUGUECHA*, T. HUININK*, I. PESHEKHODOV*, T. MATTHIAS*, J. MORITZ*, J. SCHRÖDTER*

*Institute of Forming Technology and Machines (IFUM)
Leibniz Universität Hannover
An der Universität 2, 30823 Garbsen, Germany
e-mail: schroedter@ifum.uni-hannover.de, http://www.ifum.uni-hannover.de

Key words: Magnesium, Material Characterisation, Deep Drawing, FEA.

Abstract. In the present paper, the flow behaviour of the magnesium wrought alloy AZ31 is analysed experimentally and numerically. Especial in deep drawing processes is the knowledge of the flow behaviour important. Depending on the type and size of the hardening and softening of a material, the process parameters such as temperature and sheet thickness must be adjusted to produce a flawless part. The material behaviour of magnesium is different compared to conventional steels, because the hardening and softening effects are changing highly with increasing temperature. For this purpose, yield curves were recorded experimentally at different temperatures by means of layer compression tests. Following the yield curves were converted based on the principle of the plastic work equivalence for finite element simulations (FEA). For validation, numerical simulations of the layer compression test at elevated temperature using the converted yield curve were carried out.

1 INTRODUCTION

Fast product development is an crucial element of industrial competitiveness, which has to face today's challenges such as globalization, outsourcing and short time-to-market. In major industrialized countries such as Germany, product development is made even more difficult by strict legislative regulations and high labour costs. To meet these additional challenges, while maintaining competitiveness, many new lightweight materials based on aluminium, magnesium, titanium and plastics were introduced in the last few years.

With a density of 1.74 g/cm³, magnesium is one of the lightest structural metal materials. Due to this favourable mechanic properties and abundance in nature, magnesium and its alloys have attracted a lot of interest in recent years. The use of these materials provides a weight advantage of 75 % over steel materials and 30 % over aluminium materials. Compared to plastics, magnesium has a much higher weight-specific stiffness and can be easily recycled.

Development of new products made of magnesium is time consuming because of insufficient knowledge on its technological and service properties and lack of experience regarding its processing. For this reason, the simulation-based product development is becoming especially important, as it can significantly reduce development time and cost. However, numerical simulations face new challenges caused by the new materials. Since the material behaviour of these materials is different compared to the conventional ones, new material models are to be developed and the corresponding material parameters are to be determined.

2 MAGNESIUM

Magnesium is primarily used as a construction material for light weight components due its low density of only 1.74 g/cm³. In general, magnesium materials are characterized by the following properties [1, 2, 3]:

Table 1: Properties of magnesium materials

Positive properties	Negative properties
• lowest density of all metallic construction materials at high specific strength • good damping properties • very good casting properties • virtually inexhaustible natural resources (marine, earth's crust)	• slight cold formability and toughness • limited high temperature properties (heat resistance, creep resistance) • only a few alloys available • highly susceptible to corrosion

Magnesium has a hexagonal lattice structure and therefore only demonstrates low deformability at room temperature. Investigations by Roberts [4] have proven that up to a temperature of approximately T = 200 °C, a sliding occurs only in the base plane of the hexagonal crystal lattice (Figure 1, a). More slip planes (Figure 1, b-e) are enabled at temperatures above 200 °C. This effect is due to the increased mobility of the atoms in the matrix. The additional slip planes cause the sudden increase in workability and enable the production of components manufactured by forming [5]. Components produced by forming have a fine crystalline structure and the absence of structural defects such as segregation or pores [6].

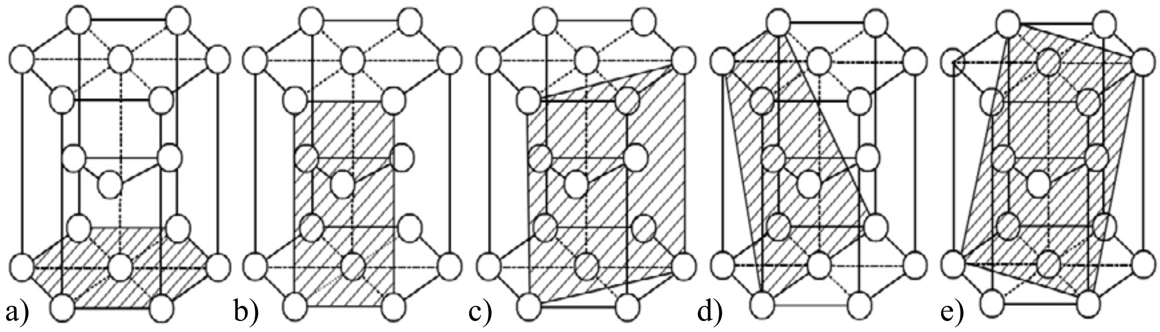


Figure 1: Slip planes of magnesium (hexagonal crystal lattice) [7]

This great potential of magnesium alloys for processing via forming is however restricted by insufficient knowledge of the specific material behaviour during forming of magnesium alloys.

Research in the field of bulk forming of magnesium alloys, their basic material properties and processing parameters as well were examined for the production of forged components [8]. Thus, extrusion is already used industrially for the production of solid and hollow profiles made of wrought magnesium.

Powder metallurgical processes for the production of precision components have also become important manufacturing processes. In the field of iron-based materials, various applications in the gear and engine construction are known. The powder metallurgical processing is another technology to process magnesium. A major advantage of this processing is the ability to develop new alloy systems [9].

In recent years, there have been successful attempts to form magnesium sheet materials at high temperatures and basic process requirements were developed. In the process, both hydroforming at high temperatures as well as the conventional deep drawing with heated tools have been used as a manufacturing process. For example, the project "ULM" consisted of examining the process chain for ultra-light components from magnesium sheet. In the frame of the project, a deep drawing tool was designed and constructed at IFUM to produce a component out of magnesium sheet.

In the project "hydro forming of magnesium sheets", the Institute of Manufacturing Technology of the Friedrich-Alexander Universität Erlangen-Nürnberg investigated the metal forming production of light weight structural components made of magnesium sheets. The material behaviour of magnesium at high temperatures was examined by means of a bulge test [10]. At Ohio State University, successful numerical studies of deep drawing processes with the magnesium alloy AZ31B have been carried out. Deep drawing experiments designed with the help of non-isothermal finite element simulations were carried out [11].

The problem of the characteristic hardening and softening behaviour of magnesium at high plastic strains is often inadequately depicted in numerical simulations. The problem is solved here with help of an experimental determination of the flow behaviour in a layer compression test and its validation with the help of a numeric analysis of the test.

3 NUMERICAL SIMULATION OF DEEP DRAWING

The use of numerical simulation for the design of deep drawing processes is becoming increasingly important. Objective of the simulation with the finite element analysis (FEA) is design of a production, quality and cost efficient process. Changes of tools during the product development can cause up to 30 % of the tool cost. To reduce the number of time-consuming and expensive field trials in this phase of product development, the simulation is used to determine whether a component can be produced as planned. Thus, the use of numerical simulations offers enormous potential to shorten the product development time. Due to the characteristics of a deep drawing process, however, large demands on the FEA are set. For high calculation accuracy, geometric nonlinearities due to large displacements, thermal-mechanical interactions between the tools and the workpiece in the form of friction and heat transfer as well as nonlinear material behaviour have to be taken into account.

In a numerical simulation of deep drawing, many parameters affect the result significantly. A change in the material property or of the sheet thickness in the forming process has a significant impact on the part performance and should be accurately predicted in numeric simulation of forming processes. The modeling of these properties, especially of the yield curve, is a major challenge in the numerical calculation of forming processes with magnesium, due to the complex relationships between thermal, mechanical and material dependent factors (Figure 2). Only the knowledge of all these parameters leads to a realistic calculation of the process.

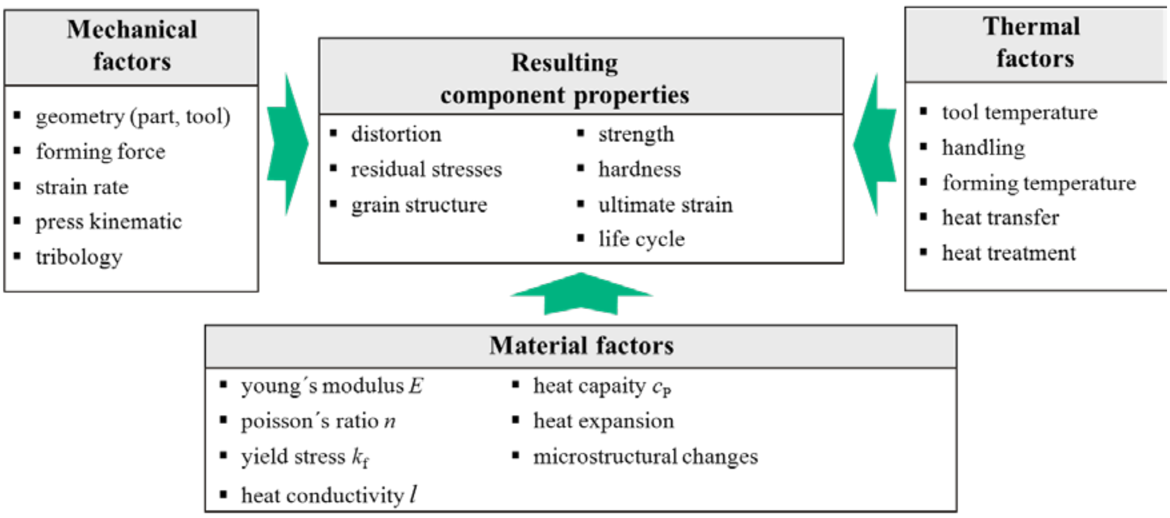


Figure 2: Factors influencing the resulting properties of deep drawn components

4 EXPERIMENTAL ANALYSIS

The yield curve, which is usually derived from the uniaxial tensile test, describes the uniaxial stress state dependent on the degree of deformation. In this case, validity is possessed only for the range of the uniform elongation. The uniaxial tensile test is therefore only usually carried out at a degree of deformation up to 0.2 as illustrated in Figure 3.

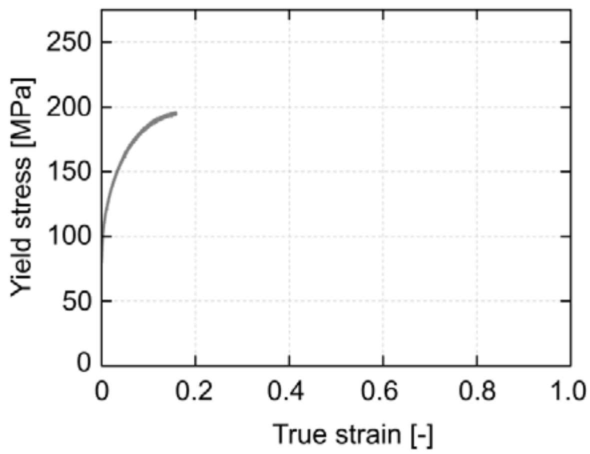


Figure 3: Yield curve of the magnesium alloy AZ31 from the uniaxial tensile test ($\varphi = 0.1$)

Generally, multiaxial stress state acts in the components during deep drawing processes, so that deformation can occur up to 1.0. Therefore, the experimentally determined yield curves are to be approximated and extended in a material model. For the approximation and the extrapolation to a deformation of 1.0, a variety of approaches are available, such as Swift, Hockett-Sherby or Ludwik Hollomon. All these approaches, however, are based on the assumption that the materials have a steadily increasing hardening. Therefore, the extrapolation of the softening behaviour in magnesium-based materials with the help of these classic approaches is not adequate. Therefore, the uniaxial tensile test is generally not suitable for the characterization of the flow properties of magnesium because the maximum deformation that can be achieved is not enough to quantify softening. A possible solution is to use a layer compression test.

4.1 Layer Compression Test

In this experiment, deformation beyond $\varphi = 1.0$ can be recorded depending on the material. The layer compression test is a special form of the classic cylinder compression test and is of great importance for the production of flat steel products.

Figure 4: Compression samples with different number of slices

The staple geometry was based on full samples from the pressure test. Compression samples are put together from a number of slices which result in a cylindrical sample form (Figure 4). In order to ensure an error-free procedure, all layer samples are thoroughly prepared. This means that all the layers are lined up in the same way in relation to the rolling direction and that good lubrication of the specimen face (e.g. graphite) between the sample and the tool is assumed.

The samples (Figure 4) were put in the centre of the heat container (Figure 5). Thereafter, it was heated up to the test temperature (20, 100, 150, 200 and 250 °C) and deformed with the tools. The core at the centre of the tools is made up of ultra-high strength steel to minimize the elastic deformation of the tools during the compression.

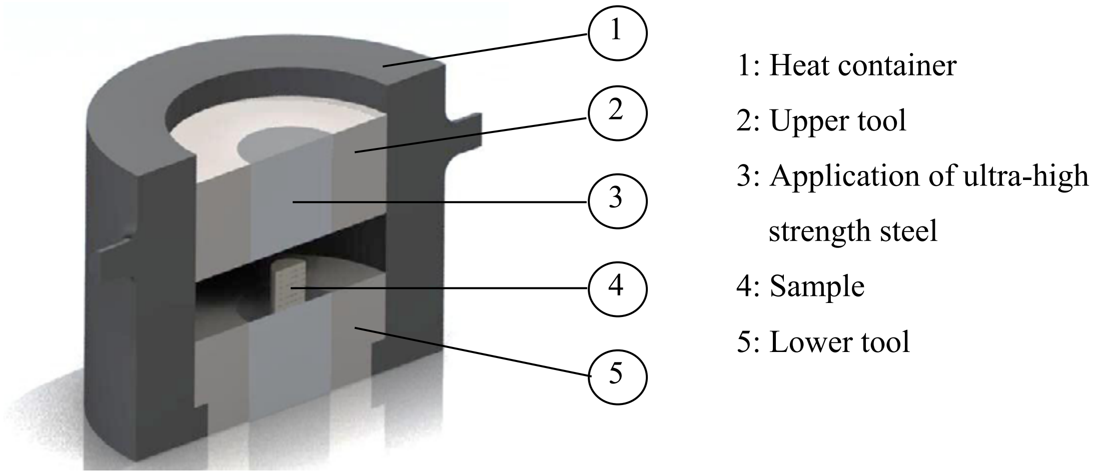


Figure 5: Heat container with integrated deformation tools

The tools are vertically guided into the heat container in order to avoid tilting. This design was integrated in a servo hydraulic deformation simulator from Instron. It has a maximum ram speed of 2.2 m/s and a compression force of 400 kN. The deformation simulator is equipped with a measuring system which has an acceleration sensor and a piezoelectric force transducer and high speed sensor. The deformed samples are shown in Figure 6.

Figure 6: Samples deformed at 200 °C

4.2 Results of the Layer Compression Test

The analysis of the experiments and the calculation of the flow behaviour were made via a special software from Instron in combination with Matlab and Excel.

The flow behaviour is thereby determined by the yield stress k_f and the true plastic strain φ. It is possible to calculate the values φ and k_f using the measured values of the compressive force F and the plastic decrease in thickness Δh under the assumption of the constant volume and a cylindrical geometry throughout the compression process.

$$k_{\mathrm{f}} = \frac{F}{A} = \frac{4 * F * (h_0 - \Delta h)}{{d_0}^2 * \pi * h_0} \quad (1)$$

$$\varphi = |\varphi|_{\max} = \left| ln \frac{h}{h_0} \right| = ln \frac{h_0}{h} \quad (2)$$

First the maximum yield stress at each forming temperature was evaluated (Figure 7).

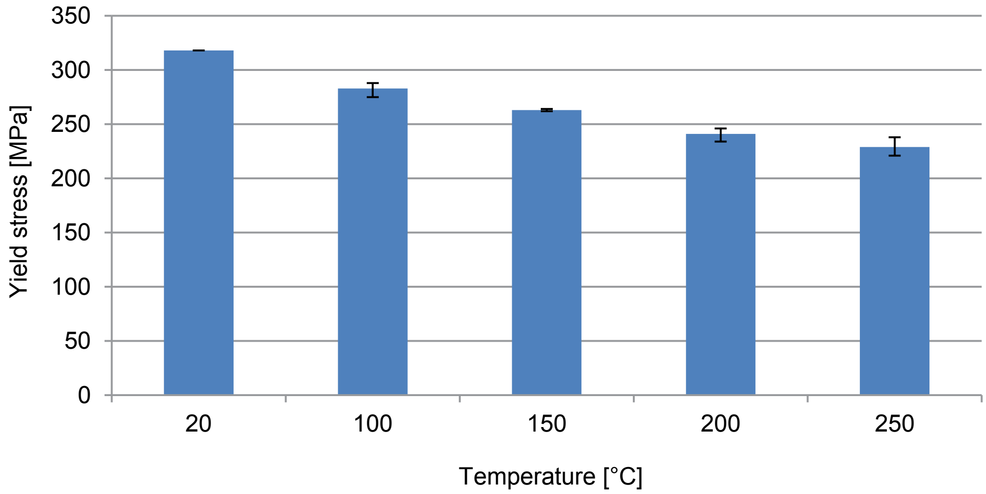


Figure 7: Mean maximum yield stress and its maximum and minimum values depending on the forming temperature

As it is shown in Figure 7 the maximum yield stress decrease with increasing temperature. Where the yield stress at 20 °C has maximum of 320 MPa, the maximum yield stress at 250 °C is only 230 MPa. However, not only the maximum yield stress but rather the achievable true strain and the flow behaviour are important for the calculation of deep drawing processes. Therefore, in the next step the yield curves were determined and analysed (Figure 8).

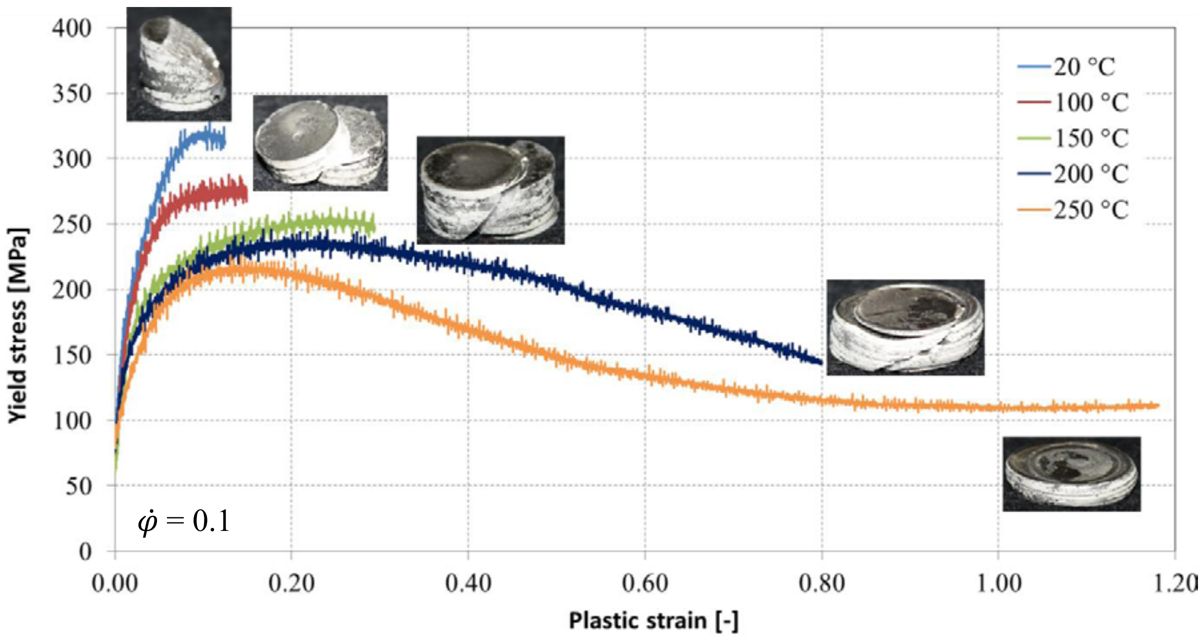
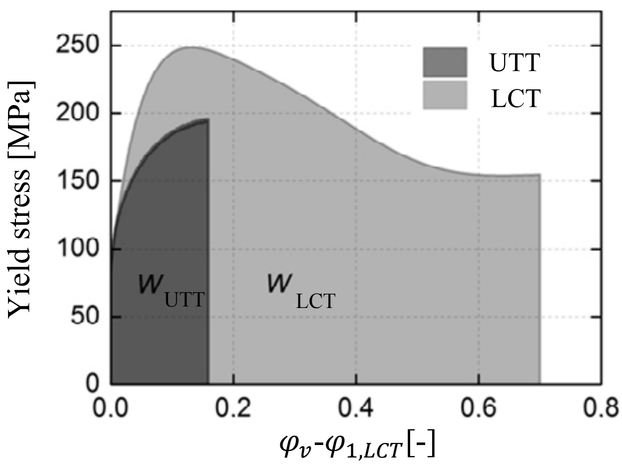


Figure 8: Yield curves of the magnesium alloy AZ31 from the layer compression test ($\dot{\varphi}$ = 0.1)

Figure 8 shows clearly the different flow behaviour dependent on the deformation temperature. With increasing temperature the maximum reachable true strain increases excessively. At a temperature of 20 °C the samples collapse at its maximum yield stress under an angle of 45°. At 150 °C the first minor softening can be determined before the sample failed at a true strain of 0.25. At a temperature of 200 °C and 250 °C a clear softening is measurable attended with a three to four time higher maximum true strain in comparison to 150 °C.

4.3 DETERMINATION OF THE FLOW CURVE AT UNIAXIAL STRESS STATE

For the use in a FEA, the yield curve at the complex stress state of the layer compression test must be converted into the equivalent plastic strain – equivalent stress curve of the uniaxial stress state. The conversion was carried out in accordance with the principle of the plastic work equivalence [12]. In the first step, the plastic work of the unit material volume was calculated for each test as a surface under the yield curves as shown in Figure 9.

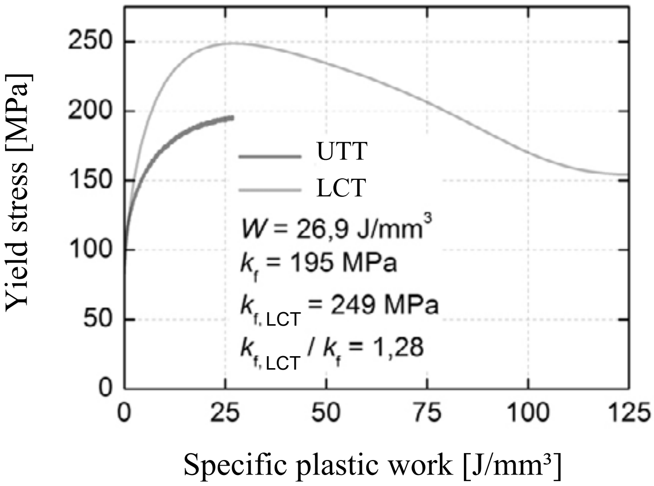


$$W_{UTT}=\int_{\varphi=0}^{\varphi_{max}} k_f d\varphi_v \qquad (3)$$

$$W_{LCT}=-\int_{\varphi 1=0}^{\varphi 1_{max}} k_{f,LCT} d\varphi_1 \qquad (4)$$

Figure 9: Left: Comparison of the yield curves from the layer compression test (LCT) and the uniaxial tensile test (UTT); Right: Corresponding specific plastic works

The obtained relations between the yield stress and specific plastic work are given in Figure 10.

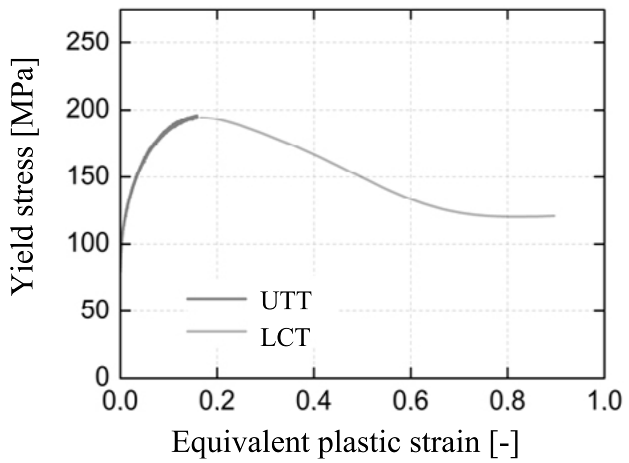


$$W_{Zug}\Big|_{A_g} = 26.9\frac{J}{mm^3} \tag{5}$$

$$\frac{k_{f,LCT}}{k_f}\Bigg|_{26.9\frac{J}{mm^3}} = 1.28 \tag{6}$$

Figure 10: Left: Yield stress over deformation energy of the layer compression test and uniaxial tensile test; Right: Calculation of the scaling factor by [12]

In the second step, for the maximum specific plastic work attained in the uniaxial tensile test the correction factor $f = kf_{LCT} / kf$ is determined. This correction factor is subsequently used to scale down the yield stress - specific plastic work curve measured in the layer compression test so that the both curves in Fig. 10 coincide at the point of the maximum specific work of the uniaxial tensile test. To fulfil the plastic work equivalence principle, the scaled yield curve of the layer compression test was then scaled up with the factor f along the x axis. The combined equivalent plastic strain – equivalent stress curve is presented in Figure 11.



$$k_f = \frac{k_{f,LCT}}{1.28} \tag{7}$$

$$\varphi_v = -1.28 \cdot \varphi_1 \tag{8}$$

Figure 11: Left: Yield stress over equivalence plastic strain of the layer compression test and uniaxial tensile test; Right: Scaling of the yield stress and the plastic strain from the LCT

Compared to the uniaxial tensile test, this method gives a uniaxial yield curve up to a significantly higher effective plastic strain. The generated yield curve meets the requirement of a deep-drawing simulation with deformation of up to 0.8 and has the advantage that an extrapolation is not necessary and therefore an error source can be avoided.

5 NUMERICAL ANALYSIS

To illustrate the potential of the converted yield curve from the layer compression test, a representative layer compression test was simulated numerically. The layer compression test at 200 °C served as a reference. The used yield curves were taken from the layer compression test and two common extrapolations (Voce and Ludwik) of the yield curve from the tensile test (Figure 11). Afterwards the results were compared with the experiment.

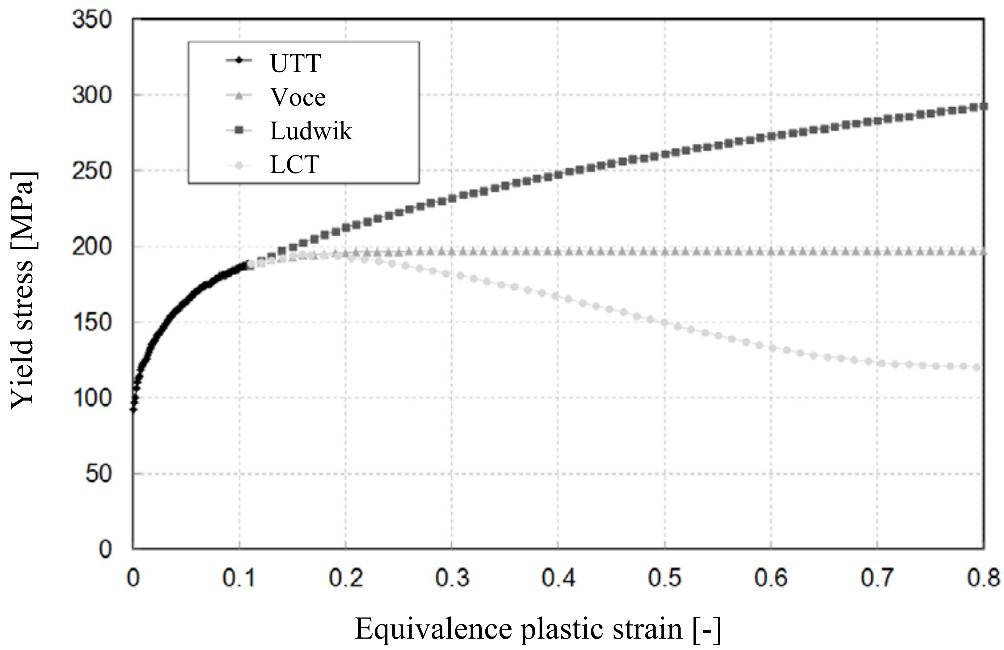


Figure 12: Yield curves used in the numerical simulation

All three observed yield curves were implemented by means of a subroutine in a commercial finite element program. The use of a subroutine is necessary because by default only steadily increasing yield curves are allowed. However, the yield curve of the layer compression test also has a softening area. The remaining model parameters are based on existing know-how.

Based on the experiments, as described in Chapter 4.1, the layer compression sample consist of seven separate layers, each with a diameter of 11 mm and a height of 1.6 mm. Figure 12 shows the result of the forming simulation in the form of the true strain of the layer compression samples before and after deformation.

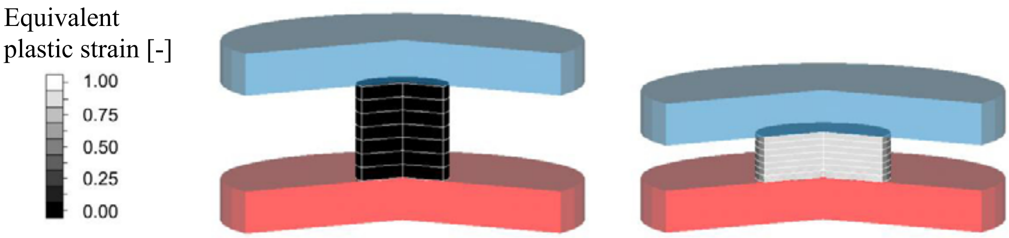


Figure 13: Computed equivalent plastic strain before and after the deformation

A comparison of the calculated and measured force-displacement curve shows clearly that the use of the yield curve of the layer compression test results in a significant improvement over the standard extrapolations (Figure 13).

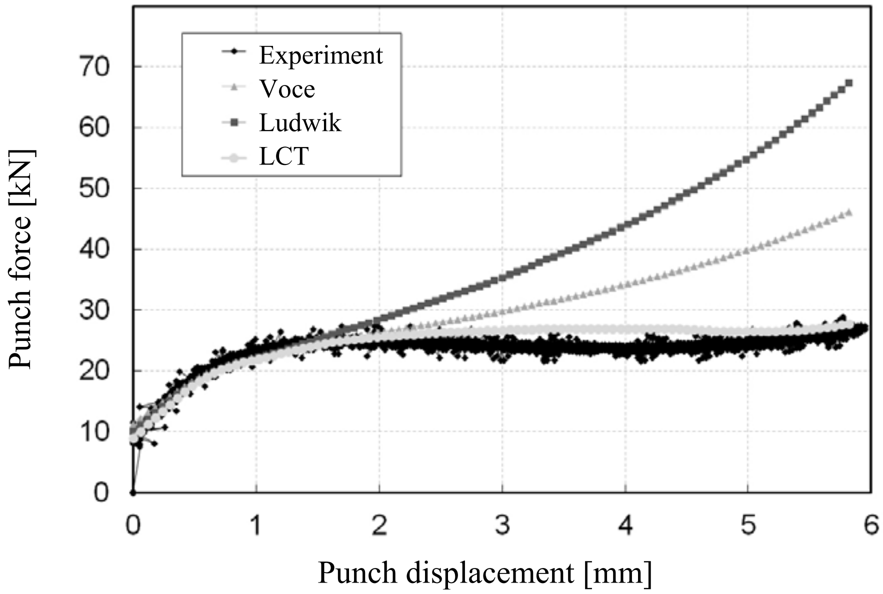


Figure 14: Computed and measured force-displacement curve in the LCT

The extrapolation of Ludwik shows, according to the yield curve, clearly excessive hardening and thus a far too high punch force. The use of the flow curve by Voce leads to a reduction of the punch force in comparison to the results by Ludwik but reflects neither the strength nor the actual characteristic curve of the experiment. With the yield curve of the layer compression test occurs a very good agreement with the experiment is achieved.

6 CONCLUSION & OUTLOOK

In the present paper, a combined yield curve for the AZ31 magnesium material at elevated temperatures was determined by tensile and layer compression tests. After a short introduction to magnesium and numerical simulation of deep drawing, the approach and the results of the layer compression test at different temperatures were presented.

The results show that the flow behaviour has the characteristic behaviour of magnesium materials, the softening at higher degrees of deformation and higher temperatures. The measured data from the tensile and the layer compression tests were combined for the integration in the numerical simulation. Subsequently, the yield curve has been implemented together with default extrapolated yield curves from the tensile test in the FEA software using a subroutine. Afterwards the layer compression test at 200 °C was simulated numerically. The results show that the standard practice leads to a significant overestimation of force. Only the use of the combined yield curve of the layer compression test results in a realistic calculation.

In the next step, the transfer to a deep drawing process will be tested. Therefore experimental as well as numerical investigation will be done.

7 ACKNOWLEDGEMENT

The authors would like to thank the German Research Foundation (DFG) for funding the project 1691/63-1.

REFERENCES

[1] Merklein, M. *Charakterisierung von Blechwerkstoffen für den Leichtbau*, Meisenbach, Bamberg, 2006.

[2] Moeller, E. *Handbuch Konstruktionswerkstoffe*, Hanser, München, (2008).

[3] Roos, E. and Maile, K. *Werkstoffkunde für Ingenieure*, Springer, Berlin, (2008).

[4] Roberts, C. S. *Magnesium and its Alloys*, Wiley, New York, (1960).

[5] Bargel, H.-J. Schulze, G. and Hilbrans, H. *Werkstoffkunde*, Springer, Berlin, (2008).

[6] Kehler, H. Bode, R. and Haddenhorst, H. *Metall*, (1995), 49:191-195.

[7] Vogt, O. *Ph.D. Thesis*, LUH Hannover, Germany, (2006).

[8] Chabbi, L. presented at *Sächsische Fachtagung Umformtechnik*, Darmstadt, Germany, November 26 -27, (1998).

[9] Haferkamp, H. Bach, F.-W. Bohling, B. and Juchmann, P. presented at 3RD *INTERNATIONAL MAGNESIUM CONFERENCE*, Manchester, United Kingdom, April 10-12, (1996).

[10] Merklein, M. Hecht, J. Hußnätter, W. and Geiger, M. *Karosserie II*, Expert Verlag, Renningen, (2006).

[11] Altan, T. Palaniswamy, H. and Ngaile, H. G. *J Mater Process Tech*, (2004), 146:52-60.

[12] Sigvant, M. Mattiasson, K. Vegter, H. and Thilderkvist, P. *Int J Mat Form*, 2, (2009).