Study on determination of flow behaviour of 6060-aluminium and AZ31-magnesium thin sheet by means of stacked compression test

M Graf\textsuperscript{1,*}, T Henseler\textsuperscript{2}, M Ullmann\textsuperscript{2}, R Kawalla\textsuperscript{2}, U Prahl\textsuperscript{2} and B Awiszus\textsuperscript{1}

\textsuperscript{1} Chemnitz University of Technology, Professorship Virtual Production Engineering, Reichenhainer Str. 70, 09126 Chemnitz, Germany
\textsuperscript{2} TU Bergakademie Freiberg, Institute of Metal Forming, Bernhard-von-Cotta-Str. 4, 09599 Freiberg, Germany

\* e-mail: marcel.graf@mb.tu-chemnitz.de

Abstract. The characterization of materials is essential for process development and process optimization. As the virtual techniques are becoming increasingly common, the material data must be identified and modelled in consideration of the process-relevant parameters (forming temperature, strain rate, sample position, main stress state and orientation). In order to ensure the model functionality, two light metal alloys – aluminium EN AW-6060 (AlMgSi0.5) and magnesium alloy AZ31 – were studied, which differ in terms of their forming behaviour and sample surface state. In order to establish a reliable test method for the determination of flow curves for thin sheet, the materials were upset in the cylindrical and stacked compression test. These were subsequently modelled by the semi-empirical Hensel-Spitell approach, for use in commercial Finite Element (FE) software.

1. Introduction

The development and optimisation of process technologies without the use of mathematical formulations and FE-methods is impossible to illustrate nowadays. In the area of metal forming, especially non-linear constitutive equations for the flow behaviour of materials with high accuracy are of great importance. In addition to the calculation of material flow and machine loads during forming, flow curves also provide information regarding hardening and softening processes in the material. As the flow behaviour is greatly influenced by material state as well, it is important to investigate the material properties for various initial states and to take these into account during each step of the process simulations [1]. For bulk materials, the calculation of flow curves from the cylindrical compression test has proven to deliver accurate material models. Alternate approaches with plane-strain compression tests, torsion tests as well as simple tension tests have been applied. Nevertheless, when considering the thin dimensions of the sheet material, commonly available mechanical testing methods have limited maximum strains.

As one of the pioneers, PAWELSKI [2] proposed to stack multiple thin specimens in order to evaluate the flow behaviour of sheet material. Here, the author’s investigations primarily focused on the influence of varying friction scenarios, during hollow cylinder compression tests. Based on that, the authors BERNRATH et al. [3] investigated layered compression tests of steel without any guides as additional stabilising methods. Conical compression tests without any lubrication have been conducted successfully. Currently named as stacked compression test or layer compression test, accurate flow
behaviour determination for steel, aluminium and magnesium sheet have been reported [4–7]. Although defined and constant friction between tool and specimen are understood to be self-evident during mechanical testing, there is no in-depth literature that gives insight regarding the friction conditions in between stacked specimens. Now, this still represents an uncertainty, because contradictory statements are found in the cited literature. As presented in [2] and [3], in order to achieve equal results for stacked versus full material compression specimens it is essential that relative movement between layers is avoided. The maximum transferable shear stress between adjacent layers must be equal to that of the full sample; otherwise, the measured flow stresses will be too low. With sufficiently high friction between adjacent layers or permanent attachment through diffusion welding processes, the determined flow stress as well as material flow remains similar to that of the full material specimen. Under these circumstances, the number of layers has shown no influence. Therefore, lubrication between the layers should be avoided. ALVES et al. [4] confirm that only sticking friction conditions at the layer interface of aluminium specimens ensures stable deformation, although the authors also tested lubrication in between layers, as suggested by MERKLEIN and KUPPERT [5]. Slipping of layers due to insufficient interface friction can be identified by a deviation in the flow curve. Concerning the magnesium alloy AZ31, flow curves from stacked compression tests by BEHRENS et al. [6] have been compared to simple tension tests. Although the authors have applied lubricant to all layer interfaces, they also state that only the flow curves have been evaluated, where the slipping of the layers to each other has not taken place. While the authors of [7] only lubricate the tool side with MoS$_2$ and not the layer interfaces, their results deliver good accordance with the flow curves from stacked compression tests and simple tension tests. Nevertheless, a very low friction coefficient between tool and specimen is known to lead to instability in stacked compression tests (specimens begin to tilt and slip) [2]. [5] and [7] both align the rolling direction in stacked compression samples in order to characterise anisotropic material behaviour. The flow curves are calculated by accounting for strains in both horizontal directions.

The friction and the surface expansion correlate directly with the surface roughness of the contact partners. However, it is significant to note which contact partner has the coarser topography. It should be that for all forming processes, the forming tool has the higher hardness. Hence, its surface structure should also be finer, so that the roughness does not dent the work piece surface and inhibit the material flow. Therefore, the roughness profile of the work piece can be levelled due to the increasing normal stresses during forming with compression stresses. With continuous forming the work piece takes over the topography of the tool. Certainly, rough surfaces can provide the lubricant with additional lubricant reservoirs as well as low contact points at the beginning of the forming process. However, if too much lubricant is trapped in the roughness cavities, it cannot escape and the roughness cannot be eliminated. In contrast, the roughness of surfaces without tool contact in the forming process, for instance during stretching, can increase. This depends not only on the initial surface but also on the near-surface microstructure. Investigations by KIENZLE et al. [8] and GRÄFENS [9] showed that the microstructure is directly proportional to the roughness change. This is due to the activation of slip and twinning systems as deformation relevant mechanisms on the microscale.

The present study addresses the fundamentals in preparation for stacked compression tests using the example of 6060-aluminium and AZ31-magnesium thin strips. The methods, with respect to initial states and material specific deformation properties, which have led to flow models are explained in detail.

2. Materials and experimental procedure

2.1. Materials

Because of the discontinuities in the literature concerning the boundary conditions to carry out the stacked compression test, firstly, an experimental study with different setups of thin discs of a commercially available aluminium alloy was conducted. These tests were carried out using extruded
3

rods of the aluminium alloy EN AW-6060 (see Table 1). The average grain size of this material is 5 µm, measured by the linear intercept method.

Table 1. Nominal chemical composition (wt.-%) of the investigated extruded EN AW-6060 determined via optical emission spectrometry (OES).

|     | Mg  | Zn  | Mn  | Zr  | Cu  | Si  | Fe  | Ca  | Sb  | Al  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|     | 0.46| 0.017| 0.05| <0.001| 0.01| 0.43| 0.21| 0.0047| 0.0127| bal.|

Furthermore, sheets of an AZ31 magnesium alloy with a thickness of 1.0 mm and the chemical composition shown in Table 2 have been upset with stacked specimens. These sheets were produced via the twin-roll casting process (TRC) with subsequent hot rolling and a final heat treatment in the pilot plant of the Institute of Metal Forming (TU Bergakademie Freiberg). The microstructure is characterised by fine recrystallised grains with an average size of 7 µm and even distribution measured by the linear intercept method.

Table 2. Nominal chemical composition (wt.-%) of the investigated AZ31 sheet determined via OES.

|     | Al  | Zn  | Mn  | Zr  | Cu  | Si  | Fe  | Ca  | Sn  | Mg  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|     | 2.99| 0.969| 0.377| 0.002| 0.001| 0.017| 0.003| <0.001| <0.005| bal.|

2.2. Setup and experimental procedure

The baseline studies to determine the boundary conditions and fitting testing parameters were performed on the extruded aluminium alloy at room temperature and a strain rate range from 0.01 to 0.5 s⁻¹. The samples were taken from the same batch. In principle, the stacked compression tests were carried out on three geometries, some of which were stacked with three, eight and nine discs. Compression tests with full cylinder aluminium samples (D10 mm x H18 mm) and the calculation of their flow curves serve as reference. In order to correlate the stacked compression test with the full sample, discs with D10 mm x H6 mm as well as D10 mm x H2 mm were machined. They were stacked in different height-diameter ratios. The thinner disc dimensions were used for the comparability of sheet metal dimensions to full samples. Special care was taken during the exact positioning of the samples. Furthermore, polished carbide plates with an average roughness of Rₐ = 0.13 µm were utilized. The aluminium sample surfaces had an average roughness of Rₐ = 0.55 µm, as a result of the machining process. To increase the roughness up to Rₐ = 1.1 µm in the contact area between two discs, selected specimen surfaces were ground with sandpaper (240 grit). The roughness was measured by the portable surface roughness tester Surftest 201 by Mitutoyo. The contact zone between the specimens and the tool surface was lubricated with a graphite solution. All surfaces were cleaned with acetone before stacking and testing.

In order to carry out isothermal compression tests, the stacked specimens as well as full cylinders were placed in upsetting cups, as shown in Figure 1. The tests were carried out in the hot forming simulator (WUMSI) at constant strain rates ranging from 0.01 s⁻¹ to 1 s⁻¹ (see [10]). In the case of hot compression tests with the magnesium alloy the upsetting cups were heated at approx. 5 K/min to the desired test temperature (250 °C to 350 °C) in an air circulation oven and held for 30 minutes. In this way, a homogeneous temperature distribution in the upsetting cups is achieved and the stacked specimens have all passed a similar temperature profile.

For the study of AZ31 magnesium thin sheets, round blanks with a diameter of D10 mm were punched out of the 1.0 mm sheet ensuring that the blanks get a straight cut edge with no bend and are subsequently stacked to a height of 15 mm (see Figure 1). The height-to-diameter ratio of 1.5 ensures the least possible influence due to friction at the tool surface, without causing the samples to buckle. Further, to ensure constant friction conditions, a graphite suspension was applied to the tool surface (carbide plates) prior to each test. As suggested by the references in literature, additional lubrication
between specimen layers was omitted in order to avoid relative movement of the layers during testing. For selected compression tests, the rolling direction of the individual sheet metal blanks was marked and aligned during stacking.

For all compression tests, the flow stress (true stress) was calculated depending on the actual cross section according to the Von Mises theory and was plotted against the logarithmic strain computed from the crosshead displacement. The bulging of the compressed specimens due to friction at the tool surface was taken into account by applying the correction function by SIEBEL [11]. The coefficients of friction assumed here can be taken from the following discussion. Softening effects due to an increase in temperature from dissipated forming energy were eliminated numerically by use of the thermodynamic temperature factor $K_\vartheta = \exp(-m_1*\vartheta)$ with $m_1=-0.00148$ °C$^{-1}$ (for Al-6060) and $m_1 = -0.00427$ °C$^{-1}$ (for AZ31). At least three parallel tests were carried out to ensure a sufficient degree of statistical certainty. The flow curves presented in the following represent the average of multiple tests.

![Example of stacked specimen](image)

**Figure 1.** Setup of stacked specimens and upsetting cup to ensure straight compression as well as an even temperature distribution during hot deformation tests.

3. Results and discussion

3.1. Modelling of flow behaviour of EN AW-6060 at room temperature

The study on the aluminium alloy was done at constant strain rates in the range of 0.01 to 0.5 s$^{-1}$. For the subsequent calculation of flow curves a friction coefficient of $\mu = 0.05$ was assumed. In Figure 2 (left) comparison between flow curves of the full cylinder specimens versus the three-layered, eight-layered and nine-layered samples is shown.

In comparison to the flow curves of the full samples, the stacked samples show a deviation of less than 5%. It can therefore be assumed that the calculation of the flow curve including numeric corrections for friction as well as dissipated energy are valid for stacked compression tests under these conditions. In the case of shear fraction of single layers or relative movement of adjacent layers, changes in the force-displacement curves are well noticeable. At this point, the termination criterion of the experiments has been reached. However, if the compression is continued until a maximum height reduction of 10 mm, the centred discs would be most often damaged (Figure 2, right). During the presented study, stacked compression tests with a diameter-height-ratio of 10:18 with 2 mm thick discs could not be realized. Very likely, the large number of slip planes has led to instability.

The modelling of the flow behaviour was done with the semi-empirical flow curve model by HENSEL and SPITTEL [12] for cold forming processes according to:

$$k_f = A \cdot e^{m_1 \vartheta} \cdot \varphi^{m_2} \cdot e^{m_3 / \varphi}$$

(1)
Figure 2. Comparison of the flow curve and the influence of the test geometry at 20 °C and a strain rate of $\phi = 0.01$ s$^{-1}$ (left) for the aluminium alloy; Geometry of the compressed sample with height reduction of 10 mm at room temperature (right).

The determined model coefficients $A$ and $m_1$-$m_4$ for the investigated aluminium alloy are shown in Table 3, resulting in a mean coefficient of determination $r^2 = 0.9785$. Therefore, a very good agreement with the experimental results can be assumed (Figure 3).

Table 3. Material specific coefficients of EN AW-6060 for the cold flow curve term.

|   | $A$  | $m_1$ | $m_2$ | $m_3$ | $m_4$ |
|---|------|-------|-------|-------|-------|
| $k_f$ | 145.734 | 0.0435 | 0.1087 | 0.0093 | -0.000079 |

Figure 3. Comparison of the experimental and modelled flow curve at room temperature for the investigated aluminium alloy at strain rates 0.1 s$^{-1}$ and 0.01 s$^{-1}$.

It should be noted, that the here developed flow model for the aluminium alloy is only valid under the investigated forming parameters temperature and strain rate. Further compression tests and investigations are necessary for conditions beyond these boundaries. In general, the chosen model can be implemented in any FE-simulation program, which allows the integration of user-defined flow stress calculation.
By applying a 2D Finite Element Method (FEM) simulation in Simufact.Forming V15, the above mentioned flow model has been used to confirm a theory that the friction coefficient between adjacent layers in the stacked compression test must be higher than the friction coefficient between the tool and the specimen (see Table 4). In the shown simulation a comparison was done by varying the friction coefficient between adjacent layers from $\mu_{\text{disc}} = 0.05$ to $\mu_{\text{disc}} = 0.2$ at a height reduction of $\Delta h = 10$ mm. The friction coefficient between the samples and the upsetting tool was set to $\mu = 0.05$ for all calculations.

Table 4. Comparison of FEM simulations by varying the friction coefficient between adjacent discs, but maintaining a constant friction coefficient $\mu_{\text{tool}} = 0.05$ of to the tool surface.

|       | $\mu_{\text{disc}} = 0.05$ | $\mu_{\text{disc}} = 0.12$ | $\mu_{\text{disc}} = 0.20$ | Effective plastic strain |
|-------|-----------------------------|-----------------------------|-----------------------------|--------------------------|
| 9 layers (\(\Delta h = 10\) mm) | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| 8 layers (\(\Delta h = 10\) mm) | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |

The results shown in Table 4 visualise precisely that lower friction coefficients between adjacent discs caused by redundant lubrication provide slip planes and thus relative movement of the layers. Therefore, these stacked samples are not valid for the calculation of flow curves as the theories for stable deformation during compression tests do not apply anymore. In practice this means, that the roughness of the discs surface (high roughness to adjacent layers) as well as of the tool surface (low roughness) must be machined adequately to ensure stable compression conditions during stacked compression tests. Lubrication is only needed at the tool-specimen-interface.

3.2. Modelling of the flow behaviour of AZ31 under hot forming conditions
The flow behaviour of the AZ31 sheet, as shown in Figure 4, was characterised at the temperatures 250 °C, 300 °C and 350 °C and at the strain rates 0.01 s$^{-1}$, 0.1 s$^{-1}$ and 1 s$^{-1}$ for logarithmic strains $\varphi < 1$. Strain hardening is followed by softening due to dynamic recrystallisation until a steady state is reached for all testing parameters. Strain hardening effects increase with strain rate and decrease with higher temperatures. The diffusion-controlled process of dynamic recrystallisation shows the opposite dependency, leading to a later steady-state with increasing strain rate and decreasing temperatures. Although the rolling direction of each layer has been aligned, the compressed sample remained circular, without any effects on in-plane anisotropy.

The external appearance and cross sections of compressed specimens have been analysed to evaluate the validity of the flow curves. Indications of horizontal or diagonal sliding of individual layers meant the exclusion of these individual experimental data from further investigation. A cross-section of a valid compression specimen is shown in Figure 5, as well. In order to correctly estimate the true friction coefficient between the stacked specimen and the tool surface, 2D-FEM simulation in Simufact.Forming V15 have been conducted here as well. As expected, due to the rough surface of the hot-rolled and heat treated AZ31 sheets the friction between adjacent layers is very high, as well as the friction at the specimen-tool-interface. Here, these conditions have led to successful stacked compression tests, as individual layers were barely exposed to relative movement.
Figure 4. Comparison of experimental results and flow curve modelling developed from stacked compression tests with AZ31 sheets at various strain rates and temperatures.

In the FEM simulation shown here, the later described flow model for AZ31 has been adapted, as well as a constant friction coefficient of $\mu_{\text{disc}} = 0.5$ between adjacent layers. As seen in Figure 5, the simulation shows good agreement with the specimen cross-section for a high friction coefficient $\mu_{\text{tool}} = 0.2$ at the specimen-tool-interface. This conceivably confirms the theory by [2], that higher friction at the specimen-tool-interface leads to more stable upsetting of stacked specimens.

![specimen cross-section](image)

Figure 5. Coloured layers from the cross-section of a tested specimen at $300 \, ^\circ\text{C}$ and $0.1 \, \text{s}^{-1}$ (determined in optical micrograph) in comparison to FEM-simulations ($\mu_{\text{disc}} = 0.5$) and varying friction coefficients $\mu_{\text{tool}}$ at the specimen-tool-interface.

For the modelling of the flow stresses of the AZ31 stacked compression tests a previously utilised approach by REICHELT et al. [13] for TRC-AZ31 was adopted. Here, a split approach was used for the description of the flow stress in the region of logarithmic strain $\phi \leq 0.2$ and $\phi > 0.2$, in order to represent the steep strain hardening followed by rapid dynamic recrystallisation and long-range steady state. In the present study, this approach was modified by changing the discrete transition to a smooth transition via a weight factor as a function of logarithmic strain, strain rate and temperature:

$$k_{\text{AZ31}} = (1-\delta_w)k_{\text{hard.}} + \delta_w k_{\text{soft.}}$$  \hfill (2)

$$\delta_w = 0.5 + \frac{1}{\pi} \tan^{-1}\left[w_1 \delta^{w_1} \phi^{w_2} \left(\phi - \phi_k \delta^{w_3} \phi^{w_4} \right)\right]$$  \hfill (3)

The coefficients $m_1$-$m_9$ for the semi-empirical flow curve model by HENSEL and SPITTEL [12] have been determined by regression of the experimental data. This approach takes into account the change in flow stress due to temperature $\theta$, logarithmic strain $\phi$ and strain rate $\dot{\phi}$.
\[ k_f = A \cdot e^{m_1 \cdot 9 \cdot \varphi^{m_2} \cdot e^{m_4 / \varphi} \cdot (1+\varphi)^{m_5 + m_6} \cdot e^{m_7 \cdot \varphi \cdot \varphi^{m_9}} \cdot (1+\varphi)^{m_6 + m_9} \cdot e^{m_7 \cdot \varphi \cdot \varphi^{m_9}}} \]  

(4)

The parameters \( w_1, w_2 \) and \( w_3 \) define the slope of the weight-function and the parameters \( \varphi_k, w_4 \) and \( w_5 \) define the location of the transition point and these were determined by regression of the experimental data (see Fehler! Verweisquelle konnte nicht gefunden werden.), as well.

**Figure 6.** Representation of the weight factor as a function of the logarithmic strain for two temperatures and two strain rates respectively.

As seen in Figure 4, the model approach with the determined coefficients presented in Table 5 is in good agreement with the experimental data. The mean coefficient of determination \( r^2 \) for all presented flow curves show a conformity > 0.9 matched to the experimental results. Hence, the material model can be applied in numeric simulations in the temperature range of 250 °C to 350 °C, at strain rates from 0.01 s\(^{-1}\) to 1 s\(^{-1}\) and logarithmic strains from 0.005 to 1.

**Table 5.** Material specific coefficients for the flow curve terms \( k_{\text{hard}} \) and \( k_{\text{soft}} \), as well as the coefficients for the weight function \( \delta_w \) determined by regression of the experimental data.

| \( a \) | A         | \( m_1 \) | \( m_2 \) | \( m_3 \) | \( m_4 \) | \( m_5 \) | \( m_6 \) | \( m_7 \) | \( m_8 \) | \( m_9 \) |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| \( k_{\text{hard}} \) | 1.203563  | -0.01248  | 0.303596  | 0.206172  | -          | -          | -2.91774  | -          | 1.671411  |           |
| \( k_{\text{soft}} \) | 2968\cdot10^6 | 0.005883  | -0.22306  | 0.064209  | -          | -          | 0.159763  | -3.37845  |           |

| \( b \) | \( \varphi_k \) | \( w_1 \) | \( w_2 \) | \( w_3 \) | \( w_4 \) | \( w_5 \) |
|--------|----------------|-----------|-----------|-----------|-----------|-----------|
| \( \delta_w \) | 0.434768       | 0.177448  | 0.693086  | 0.147218  | -0.087559 | -0.018842 |

**4. Conclusion**

In the presented study stacked compression tests for 6060-aluminium and AZ31-magnesium alloys were realised successfully, in order to provide material-state-specific flow models for numeric simulations. The following conclusions and handling recommendations can be derived from the presented stacked compression test results:
The authors have concluded from the literature research, that high friction between adjacent layers in combination with low friction to the upsetting tool prohibits relative layer movement and ensured stable upsetting.

A flow curve model for the hot deformation behaviour of 1.0 mm AZ31 sheet was presented for logarithmic strains 0.005 to 1, as well as a flow curve model for 6060-aluminium extruded rod at room temperature for logarithmic strains 0.005 to 0.6.

A study on aluminium disks with different height-diameter-ratios, as well as parallel FEM-simulations have led to the conclusion that the friction coefficient between adjacent layers needs to be greater than the friction coefficient at the specimen-tool-interface.

As a result of the rough surface quality of the hot rolled AZ31 sheets, relative layer movement did not occur and stable upsetting of stacked specimens was achieved.

Acknowledgments

The authors thank the German Research Foundation (DFG) for the financial support of the project “Characterisation and modelling of the biaxial material behaviour of twin-roll-cast, hot rolled and annealed AZ31 sheets” (AW6/34-1; UL471/3-1). This research has the DFG grant number 396576920.

References

[1] Graf M, Ullmann M, Korpala G and Kawalla R 2013 Materialkennwerte als Basis für die numerische Simulation von Warmumformprozessen Proceedings 22. Verformungskundliches Kolloquium (Planeralm) ed B. Buchmayr pp 49–55

[2] Pawelski O 1967 Über das Stauchen von Hohlzylindern und seine Eignung zur Bestimmung der Formänderungsfestigkeit dünner Bleche Archiv für das Eisenhüttenwesen 38 pp 437–442

[3] Bernrath G, Volles R and Kopp R 2006 Multi-Layer Compression Tests under Hot Forming Conditions steel research international Issue 77 pp 265–270

[4] Alves L M, Nielsen C V and Martins P A F 2011 Revisiting the Fundamentals and Capabilities of the Stack Compression Test Exp Mech 51 pp 1565–1572

[5] Merklein M and Kuppert A 2009 A method for the layer compression test considering the anisotropic material behavior Int. J Mater Form 2 pp 483–486

[6] Behrens B-A, Bouguecha A, Bonk C and Dykiert M 2017 Experimental Characterization and Material Modelling of an AZ31 Magnesium Sheet Alloy at Elevated Temperatures under Consideration of the Tension-Compression Asymmetry J. Phys.: Conf. Ser 896 2019.

[7] Herzig N, Abdel-Malek S and Meyer L W 2010 Experimentelle Ermittlung und Modellierung dynamischer Fließortkurven an Blechwerkstoffen Proc. 9. LS-DYNA Forum (Bamberg) pp 29-40

[8] Kienzle O and Mietzner K 1967 Atlas umgeformter metallischer Oberflächen (Berlin, Heidelberg: Springer Verlag)

[9] Gräfen H 1993 Lexikon Werkstofftechnik: Berichtigter Nachdruck ed H Gräfen (Berlin, Heidelberg: Springer Verlag)

[10] Henseler T, Ullmann M, Korpala G, Klimaszewska K, Kawalla R and Berge F 2017 Influence of Deformation Controlled Strain Rate on Tensile and Compression Behaviour of Magnesium and Steel Wire Mater. Sci. Forum 892 pp 89–96

[11] Siebel E 1932 Die Formgebung im bildsamen Zustande, theoretische Grundlagen der technischen Formgebungsverfahren (Düsseldorf: Stahleisen)

[12] Hensel A and Spittel T 1978 Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren (Leipzig: Deutscher Verlag für Grundstoffindustrie)

[13] Reichelt S, Neh K, Helbig M and Ullmann M 2016 On the Importance of Accurate Material Data for Modeling and Simulation of Forming Processes Proceedings of the 19th International ESAFORM Conference on Material Forming (Nantes, France) ed F Chinesta, E Cueto, E Abisset-Chavanne (Melville, N. Y.: American Institute of Physics)