DOI 10.1002/mawe.201100720

Modeling of the material behavior during hot hydroforming

Modellierung des Materialverhaltens während der Warm-Innenhochdruck-Umformung

D. Elsenheimer, C. Taplick, P. Groche

For the purpose of numerically simulating metal forming processes, material data are necessary, determined by testing procedures similar to the particular process. The new technology of hot tube bulge tests has been introduced recently, fulfilling the requirements of material data determination for hot hydroforming. Based on measurement data gained by this technology, selected constitutive relations for approximating the flow stress depending on temperature, strain rate and logarithmic strain were parameterized applying linear regression analysis. Using the material law with the best approximation quality among the regarded equations, a numerical simulation of an exemplary forming process was accomplished. A comparison between the experimentally obtained geometry after a hot hydroforming process and the prediction by numerical analysis is used for evaluating the quality and applicability of the determined material data for this kind of process. Additionally, a process simulation, using extrapolated material data from compression tests is presented to visualize the influence of the testing procedure on the resulting part geometry prediction.

Keywords: hot hydro forming / material properties / constitutive law / hot tube bulge test

Für die numerische Abbildung von Umformprozessen werden Materialdaten benötigt. Das Verfahren zur Ermittlung dieser Parameter sollte sich am jeweiligen Prozess orientieren. Der Warm-Berstversuch stellt eine neue Technologie dar, um Materialdaten für die Warm-Innenhochdruck-Umformung zu gewinnen und der Anforderung nach einem prozessnahen Prüfverfahren gerecht zu werden. Basierend auf Messwerten werden unter Zuhilfenahme der linearen Regression grundlegende Einflüsse von Temperatur, Dehnrate und Umformgrad auf die Fließspannung in parametrischer Form gewonnen. Dabei findet das Materialgesetz mit der höchsten Approximationsgüte unter den aufgestellten Gleichungen Anwendung für die Simulation des Umformprozesses. Durch den Vergleich einer im Warm-Innenhochdruck Verfahren gewonnen Geometrie und der Vorhersage durch die numerische Analyse wird die Qualität und Anwendbarkeit der Materialdaten für diesen Prozess unter Beweis gestellt. Zusätzlich stellt die Prozesssimulation mit extrapolierten Materialdaten aus dem konkurrierenden Stauchversuch den Einfluss des gewählten Testverfahrens auf die Vorhersagbarkeit der späteren Bauteilgeometrie dar.

Schlüsselwörter: Warm-Innenhochdruck-Umformung / Materialeigenschaften / Materialgesetz / Warm-Berstversuch

1 Introduction

In the field of metal forming technologies, the uniaxial tensile test is the most common technology for material characterization. However, considering hydroforming processes, material data obtained by tensile tests is limited concerning its transferability to tubular shaped blank parts. This limitation is caused by the influence of the manufacturing process a tube has been subjected to on one hand. For example, tubes produced by a bending process reached 16% average circumferential expansion, while roll formed tubes of the same material and geometry only enabled a maximum circumferential expansion of 10%, as Groche et al. (2005) investigated. On the other hand, hydroforming applications often enable higher than logarithmic strain observed in uniaxial tensile tests. Therefore, when tensile test data are used for the prediction of hydroforming processes, extrapolation errors may occur. Thirdly, in tensile tests the stress state is uniaxial, whereas in hydroforming applications multiaxial loading and resulting stress states appear, as Yingyot et al. (2006) referred.

Hence, other experimental setups have been proposed to gain material data close to the real strain state occurring in tubes during hydroforming.

Technische Universität Darmstadt, Institute for Production Engineering and Forming Machines, Petersenstraße 30, 64287 Darmstadt

Correspondence author: Christoph Taplick, Technische Universität Darmstadt, Institute for Production Engineering and Forming Machines, Petersenstraße 30, 64287 Darmstadt
E-mail: taplick@ptu.tu-darmstadt.de

One applicable technology, providing higher logarithmic strain than tensile tests and higher similarity to hydroforming applications in terms of occurring stress as well as strain states is the hydraulic bulge test. In this setup, a sheet metal specimen gets clamped in a circular die in order to prevent material flow in radial direction. The specimen is then loaded by hydraulic pressure on one side, which leads to a spherical deformation. By measuring the pressure and the corresponding deformation, stress-strain-curves can be generated. This procedure can be accomplished at elevated temperatures by using heated pressure media, as reported by Novotny and Geiger (2003) for aluminum sheets up to 300 °C. In this application, heated pressure media as well as a heated tool were applied. Kaya et al. (2008) refer to bulge testing of magnesium sheets at elevated temperatures, using a submerged tool to reach a constant temperature distribution in the specimen sheet. The applied pressure medium allows testing temperatures up to 280 °C. Liewald and Kappes (2009) describe an experimental setup of the bulge test using gas as pressure medium and therefore conducted investigations in the hot temperature range. Results are presented for magnesium sheets at 400 °C.

Groche et al. (2002) describe the possibility of realizing constant strain rates in bulge tests by determining the volume flow progression basing on FE-Analyses. Rauscher et al. (2005) accomplished the same property by controlling the pressure/ time – progression on the basis of process simulations.

As a further step towards emulating the conditions in hydroforming processes, a tube bulge test with fixed ends was established by Hielscher (2000). During this experiment, tubes, which are end-fixed, expand by internal pressure until they fail by bursting. The internal pressure and the radial expansion are recorded. By means of these data, tube flow curves can be calculated, as for example von Breitenbach (2007) described, basing on the von-Mises-criteria. For this calculation, it is necessary to create a plain-strain-state in the tube's wall during the bulge tests, with no strain occurring in axial direction. Based on the postulate of constant volume, the strain in radial direction can be calculated. Using the radial and circumferential strain values, the equivalent strain according to von Mises can be determined. The equivalent stress value is also calculated according to von Mises. The stress components implemented in this calculation are gained from the internal pressure by Barlow's formula, where the stress component in radial direction is neglected. This is acceptable because of the high diameter versus wall thickness ratio of the regarded tubes.

Bortot, Ceretti and Giardini (2008) also presented an analytical approach describing the occurring stress state during tube bulge tests. Conducted experiments require their interruption at certain pressure states in order to measure the bulge geometry.

The temperature range of the tube bulge testing technique was extended into the area of warm forming by Dörr (2006), using heat transfer oil as pressure medium, which allows for process temperatures up to approximately 250 °C. Tube bulging experiments on magnesium tubes at temperatures up to 450 °C are reported by Krishnamurthy et al. (2004). In the applied experimental setup, tubes were heated inductively and expanded by internal nitrogen pressure. The resulting strain state in the tube wall is three-dimensional with the axial strains averaging 50% of the amount in longitudinal direction. An average strain rate of 0.001 s^{-1} was achieved.

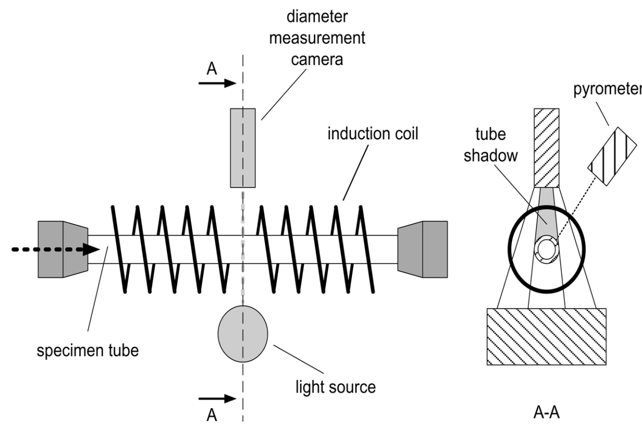

Figure 1. Schematic of the hot bulge test stand.

Bild 1. Schema des Warm-Berstprüfstands.

The mentioned testing procedures are respectively adapted to certain types of blank parts (tubes or sheets), temperature and strain rate ranges and therefore refer to certain forming processes. The specific properties of hot tube hydroforming processes are not covered by these technologies.

The recently developed hot tube bulge testing technology, which has been described by Elsenheimer and Groche (2009), enables the burst testing of tubes at controlled temperature and equivalent strain rate at temperatures only limited by the blank material's melting point. Therefore it is an appropriate procedure for the determination of material properties for hot hydroforming. *Fig.1* shows a schematic of the realized testing system.

In this setup, the specimen tube gets heated by an induction coil. Temperature and tube diameter are constantly being measured by optical devices. The internal pressure, generated by pressurized air, is controlled in such a way that the equivalent strain rate in the tube's axial center reaches a constant target value. *Fig. 2* illustrates an exemplary progression of the strain rate and the corresponding internal pressure.

A plane strain state is reached, exhibiting negligible small strain in axial direction. Based on this condition, tube flow curves of constant strain rate and temperature can be calculated by the equations of von Breitenbach (2007) in combination with a developed cooling compensation method (Elsenheimer and Groche (2009)).

Comprehensive investigations have been made with the realized testing equipment, focusing on tubes made of the aluminum alloy AlMgSi0.5 (EN-AW 6060). Strain rates between 0.05 s^{-1} and 0.15 s^{-1} were investigated at temperatures between 435 °C and 580 °C. Exemplary results, exhibiting the influences of temperature and strain rate on the flow stress are shown in *Fig. 3* and *Fig. 4.*

Obviously, the flow stress increases with increasing strain rate, while higher temperatures lead to a softening of the material. Starting from a logarithmic strain of approximately 0.05, the stress-strain-graphs possess a nearly linear progression. At this strain value the target strain rate is usually reached for the first time, Fig. 2. Therefore the experimentally gained flow curves

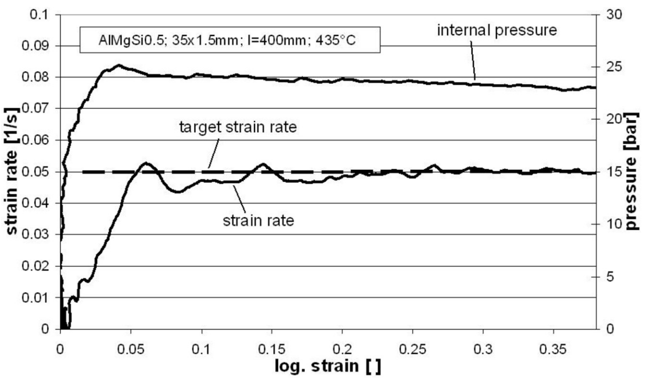

Figure 2. Controlled strain rate and corresponding internal pressure (Elsenheimer and Groche (2009)).

Bild 2. Geregelte Umformgeschwindigkeit und korrespondierender Innendruck (Elsenheimer und Groche (2009)).

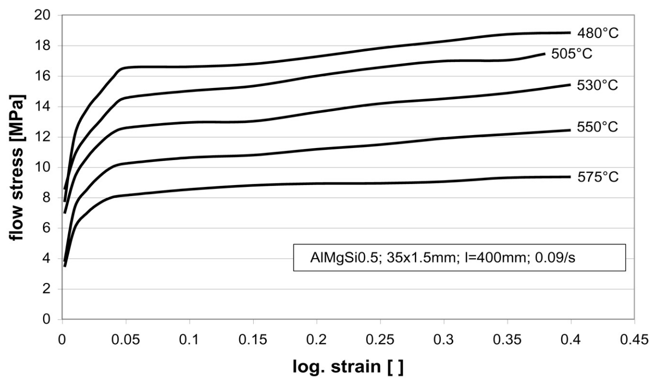

Figure 4. Temperature-dependent flow stress (Elsenheimer and Groche (2009)).

Bild 4. Temperatureinfluss auf das Fließverhalten (Elsenheimer und Groche (2009)).

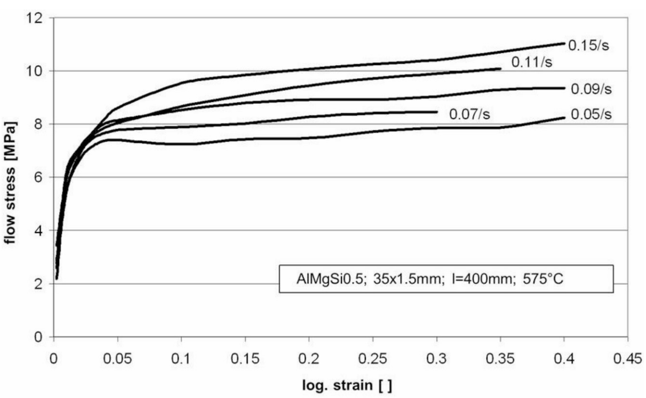

Figure 3. Strain rate-dependent flow stress (Elsenheimer and Groche (2009)).

Bild 3. Einfluss der Umformgeschwindigkeit auf das Fließverhalten (Elsenheimer und Groche (2009)).

may be considered as strain-rate-constant starting from a logarithmic strain of 0.05.

The present paper focuses on the processing and the application of material data established by hot tube bulge tests for finite element simulation of hot hydroforming processes.

2 Tube flow curve approximation

The usage of experimentally gained material data in numerical simulations requires the feeding of this data into the simulation software. This can be accomplished by entering tabular data. The material behavior in between the entered discrete data sets has to be determined by interpolation. A method appearing smarter than entering tabular data is describing the material behavior by analytical relations. This enables the continuous definition of the material properties without the necessity of interpolation. Furthermore, the procedure of defining the material within the FE-software gets considerably simplified by this method.

Several approaches for the analytical description of material behavior during deformation have been proposed in the recent years. Depending on the particular approach, different parameters are being regarded. For the purpose of describing the flow stress (k_f) under the combined influences of temperature (T), logarithmic strain (φ) and strain rate ($\dot{\varphi}$), three applicable equations have been selected, *Table 1.*

Table 1. Selected constitutive equations for the flow stress, considering strain, strain rate and temperature

Tabelle 1. Ausgewählte Approximationsgleichungen zur Materialbeschreibung unter Beachtung von Umformgrad, Umformgeschwindigkeit und Temperatur

$k_f = A_0 \cdot e^{A_1 \cdot T} \cdot \dot{\varphi}^{A_2} \cdot \varphi^{A_3} \cdot e^{A_4 \cdot \varphi}$	(1)	Hensel and Spittel (1978)
$k_f = A_0 \cdot \varphi^{A_3} \cdot \dot{\varphi}^{A_2} \cdot \varphi^{A_3} \cdot e^{(-A_3 \cdot T)}$	(2)	Hodgson and Hajduk 1987 (in Meyer, Weise and Hahn (1997))
$k_f = A_0 \cdot \varphi^{A_1} \cdot \dot{\varphi}^{A_2} \cdot T^{A_3}$	(3)	Heller (1992)

These equations describe the equivalent flow stress depending on the previously mentioned parameters and a number of coefficients A_n which have to be adapted in order to provide the best quality of the flow stress prediction. This adaptation can be accomplished by means of regression analysis. Therefore, the equation has to be linearized, as shown by expression (4) for equation (1):

$$\ln(k_f) = \ln(A_0) + A_1 \cdot T + A_2 \cdot \ln(\dot{\varphi}) + A_3 \cdot \ln(\varphi) + A_4 \cdot \varphi \quad (4)$$

Utilizing the recorded data of n experiments, a linear system of n equations can be set up:

$$\begin{pmatrix} 1 & T_1 & \ln(\dot{\varphi}_1) & \ln(\varphi_1) & \varphi_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & T_n & \ln(\dot{\varphi}_n) & \ln(\varphi_n) & \varphi_n \end{pmatrix} \begin{pmatrix} \ln(A_0) \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{pmatrix} = \begin{pmatrix} \ln(k_{f1}) \\ \cdot \\ \cdot \\ \cdot \\ \ln(k_{fn}) \end{pmatrix} \quad (5)$$

This mathematical problem can be resolved applying the method of least square fit.

The study described in this paper is focused on the Aluminum alloy AlMgSi0.5 (EN-AW 6060). Parameter adaptations by regression analyses of the introduced equations (1)…(3), based on experimental data, lead to the results listed in *Table 2.*

Table 2. Results of regression analyses based on experimental data

Tabelle 2. Aus Versuchsdaten ermittelte Ergebnisse der Regressionsanalyse

Specimen geometry	
Tube material	AlMgSi0.5
Tube diameter	35 mm
Wall thickness	1.5 mm
Tube length	400 mm
Adapted equations	
$k_f = 1796,33 \cdot e^{(-0,0083 \cdot T)} \cdot \dot{\varphi}^{0,2493 A_2} \cdot \varphi^{0,0183} \cdot e^{0,4572 \cdot \varphi}$	Hensel and Spittel
$k_f = 2260 \cdot \varphi^{0,0945} \cdot \dot{\varphi}^{0,2492} \cdot e^{(-0,0083 \cdot T)}$	Hodgson and Hajduk
$k_f = 1,058 \cdot 10^{13} \cdot \varphi^{0,0945} \cdot \dot{\varphi}^{0,2475} \cdot T^{-4,2513}$	Heller

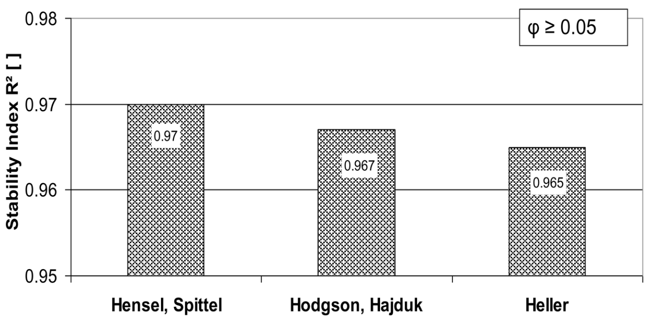

Figure 5. Comparison of stability indexes.

Bild 5. Vergleich der ermittelten Bestimmtheitsmaße.

For evaluating the selected equations, the stability index R2 was checked. This statistical value, ranging between 0 and 1, is a measure for the approximation quality of an analytical description, whereas $R^2 = 1$ represents a perfect approximation. *Fig. 5* compares the calculated stability indexes to each other, showing the best approximation quality for the equation according to Hensel and Spittel.

In *Fig. 6*, a comparison between exemplary measured and calculated flow curves is given for the Hensel/Spittel-equation. Obviously, there is a good agreement of the approximated and the real material behavior as the stability index examination already predicted.

3 Application of the established constitutive equation

In order to assess the applicability of the material data gained by means of the hot tube bulge test, a comparison between a prediction based on FE-simulations using the constitutive equation for describing the material behavior and a hot hydroformed part was accomplished. *Fig. 7* illustrates the part geometry. The semifinished part measured 35 mm diameter × 1.5 mm wall thickness.

Firstly an appropriate combination of temperature distributions (tube and die), internal pressure- and axial feed-profile was identified in prototyping experiments.

In the eventual combination, the die was heated up to 590 °C, while the tube's center temperature was 565 °C. The progressions of internal pressure and axial feed over the process time are shown in *Fig. 8*.

The progression curves as well as the temperature distributions were determined empirically. For this purpose, at first the pressure being required for inducing first plastical deformation was identified experimentally. Using this pressure, in subsequent experiments the axial feed was raised until tube buckling occurred. From this point on, the calibration process was started by raising the internal pressure while the tube ends were fixed. This experience driven approach in this case is applicable, since the focus of the experiments is not to reach a maximum logarithmic strain, but to produce a part geometry reproducibly for further comparisons with numerical simulation results.

Using the constitutive equation of Hensel and Spittel for modeling the material behavior, a fully thermo mechanically coupled FE-Simulation of the forming process, considering the process parameter combination used in the real forming process was set up using the software MSC Marc/Mentat. The physical and numerical properties listed in *table 3* were applied.

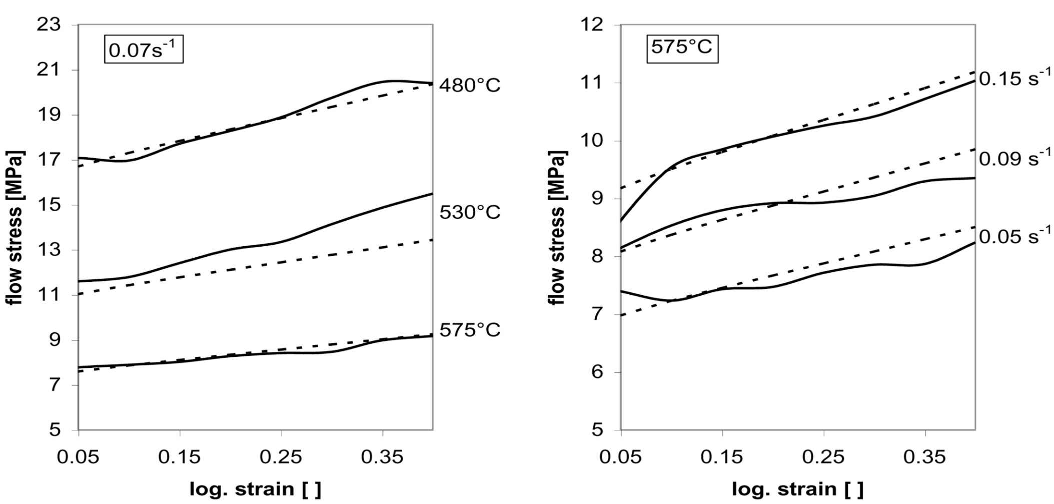

Figure 6. Measured (solid lines) and calculated (dotted lines) flow curves of AlMgSi0.5 tubes.

Bild 6. Gemessene (durchgezogene Linie) und approximierte (gepunktete Linie) Fließkurven von Rohren der Legierung AlMgSi0,5.

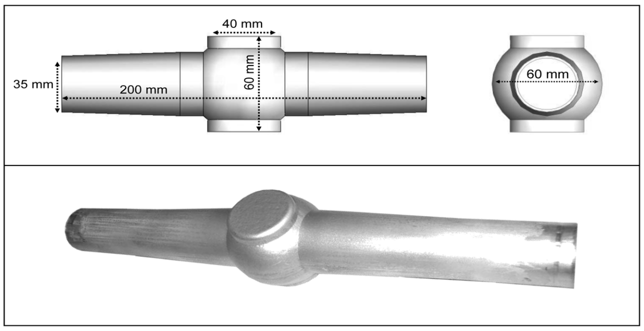

Figure 7. Demonstration part geometry. Top: Dimensions, bottom: Realized part.

Bild 7. Geometrie des Demonstrators. Oben: Abmessungen, unten: erzieltes Bauteil.

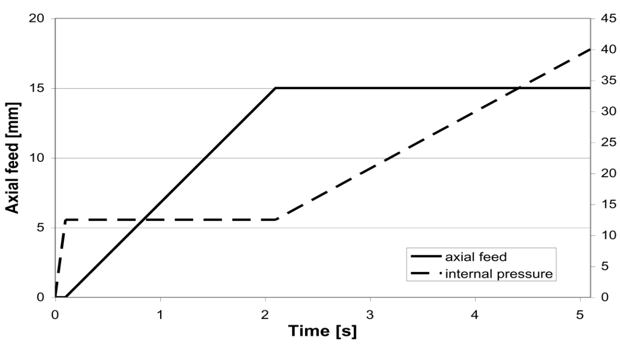

Figure 8. Axial feed and internal pressure progressions.

Bild 8. Verlauf von axialem Nachschiebeweg und Innendruck.

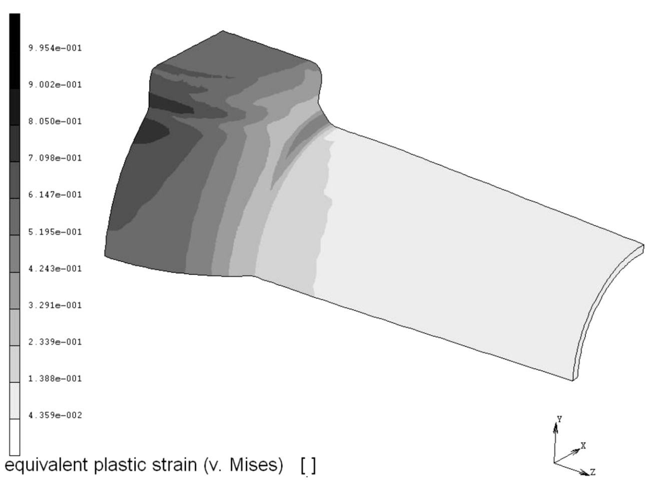

Figure 9. Result of the numerical process simulation.

Bild 9. Ergebnis der numerischen Prozesssimulation.

Utilizing symmetrical properties of the demonstration part geometry, the computation time could be reduced by modeling only 1/8 of the geometry and applying boundary conditions, representing the complete part geometry. The result of the numerical simulation is shown in *Fig. 9*.

For the purpose of directly comparing the results of the numerical simulation and the real forming process, the system

Table 3. Physical and numerical properties applied in the FE – simulation

Tabelle 3. Physikalische und numerische Eigenschaften in der FE-Simulation

Meshing	
Element type	Fully intergated brick elements, 8 nodes, 8 integration points, assumed strain formulation for improved modeling of bending behaviour
General material data AlMgSi0.5	
Young's modulus	70,000 MPa
Poisson ratio	0.3
Mass density	2.63 g/cm^3
Thermal conductivity	200 W/m/°K
Specific heat capacity	960 J/kg/K
Emission coefficient (graphite based lubricant)	0.8
Contact properties	
Friction coefficient tube/die	0.05
Heat convection tube/die	3 W/m^2/°K
Heat convection tube/environment	0.01 W/m^2/°K

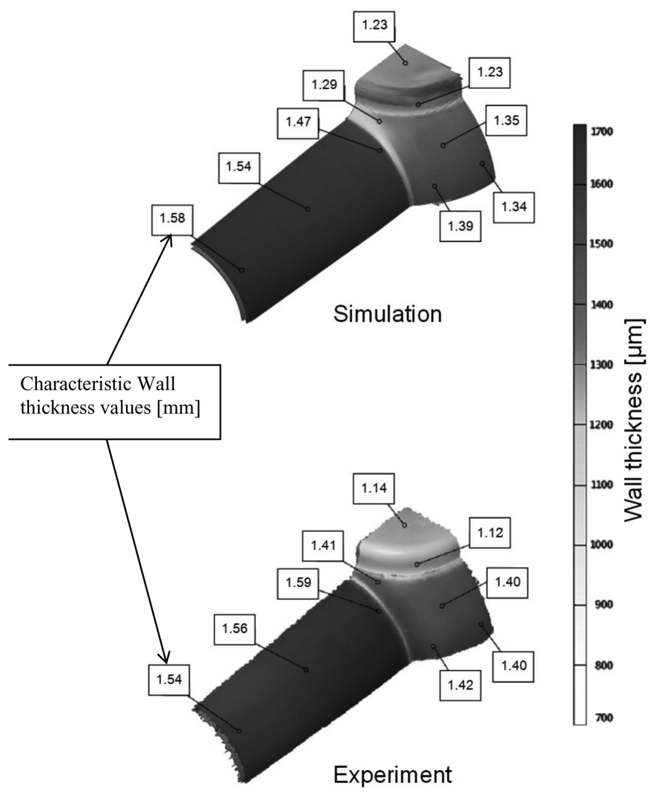

Figure 10. Comparison between FE-simulation and realized part geometry.

Bild 10. Vergleich zwischen FE-Simulation und realer Bauteilgeometrie.

Table 4. Tabular comparison between simulation and experiment concerning the wall thickness distribution

Tabelle 4. Vergleich der Wanddickenverteilung zwischen Simulation und Experiment

measuring point	simulation [mm]	experiment [mm]	deviation
1	1.58	1.54	−2.6%
2	1.54	1.56	1.3%
3	1.47	1.59	7.5%
4	1.29	1.41	8.5%
5	1.23	1.14	−7.9%
6	1.23	1.12	−9.8%
7	1.35	1.4	3.6%
8	1.34	1.4	4.3%
9	1.39	1.42	2.1%

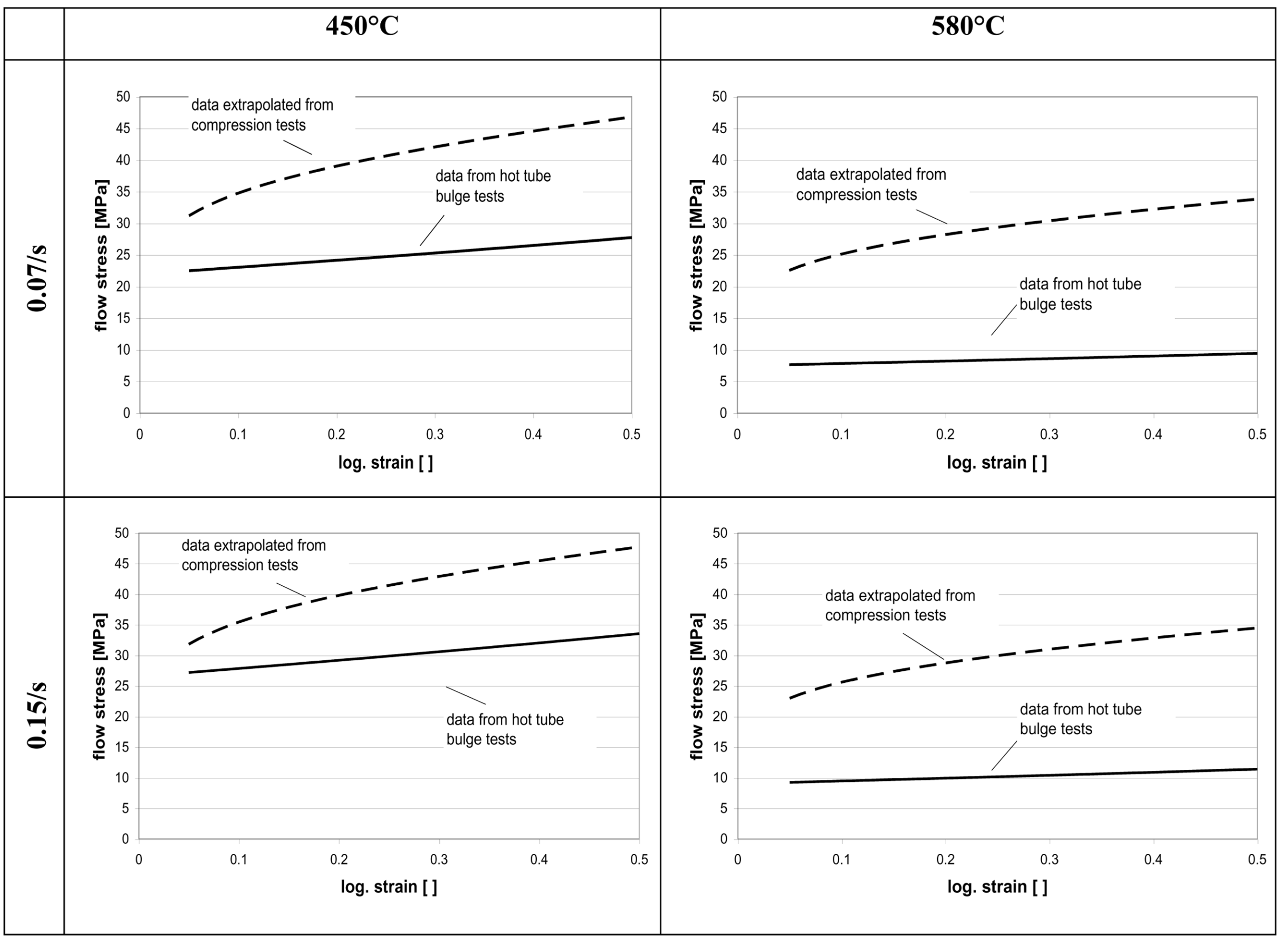

Figure 11. Comparison of flow curves extrapolated from warm compression tests and determined by hot tube bulge tests.

Bild 11. Vergleich der Fließkurven von extrapolierten Warm-Stauchversuchen mit Warm-Berstversuchen.

GOM ATOS III was applied. This optical measurement device is able to digitize three-dimensional geometries and compute a representation in form of a 3-D scatter plot. This plot can subsequently be meshed by tetrahedron shaped elements. The system also allows for importing geometrical data such as finite element simulation results. A number of tools for interpreting the data is available.

For the purpose of evaluating the gained material data, a comparison of the wall thickness distribution of the formed part is useful. This distribution mainly results from the material's resistance against deformation, since in hydroforming applications only the outer shape of the formed geometry is defined by the die. Therefore, if a simulation provides a good prediction quality concerning the wall thickness distribution, evidence of high quality of the material behavior modeling can be deduced.

In *Fig. 10*, the results of the numerical simulation and the realized part are opposed to each other. The wall thickness is evaluated at exemplary measuring points. The detailed comparison given in table 4 approves the high consistency of experiment and simulation.

The analyzed FE-model, comprising a material definition basing on the developed hot tube bulge test technology and described by the constitutive equation of Hensel and Spittel is capable of predicting the correct wall thickness distribution with a deviation of 5.3% in average.

4 Comparison of material data determined by different testing techniques

In order to evaluate the influence of the particularly applied testing procedure on the determined flow curves, a comparison between material data gained by compression tests, extrapolated from the warm into the hot temperature range and by hot tube bulge tests was conducted. Representing compression tests, flow curves published by Doege et al. (1986) were used. In this flow data compilation, data of the material AlMgSi0.5 is given for the temperature range 20 °C…250 °C at the two strain rates 0.25 s^{-1} and 10 s^{-1}. By means of a regression analysis, extrapolation of this data into a higher temperature range, based on the Hensel/Spittel-Approach was made, leading to the following result:

$$k_f = 156.93 \cdot e^{-0.0025 \cdot T} \cdot \dot{\varphi}^{0.0261} \cdot \varphi^{0.1434} \cdot e^{0.1673 \cdot \varphi} \qquad (6)$$

For the exemplary temperatures 480 °C and 580 °C as well as the strain rates 0.07 s^{-1} and 0.15 s^{-1}, a direct comparison of the flow curves extrapolated from compression tests and measured in hot tube bulge tests is given in *Fig. 11*.

Obviously, determination of flow curves by compression tests and extrapolation into the hot temperature range leads to huge deviations compared to flow curves from hot tube bulge tests. This is because the technique of compression tests possesses more similarity to bulk forming processes than to those of sheet metal forming on one hand. On the other hand it is assumed that the extrapolation process falsifies the data additionally. The potential for errors, when extrapolated data from testing procedures with small similarity to the regarded process are used as input for numerical process simulations, *Fig. 12*. This figure shows the result of the same FE-simulation leading to the results shown in Fig. 9, however the material data set is the extrapolated one.

Apparently there are huge deviations between this prediction and the realized part Fig. 7. This is due to the flow curves based on compression test data tending to too high stress levels.

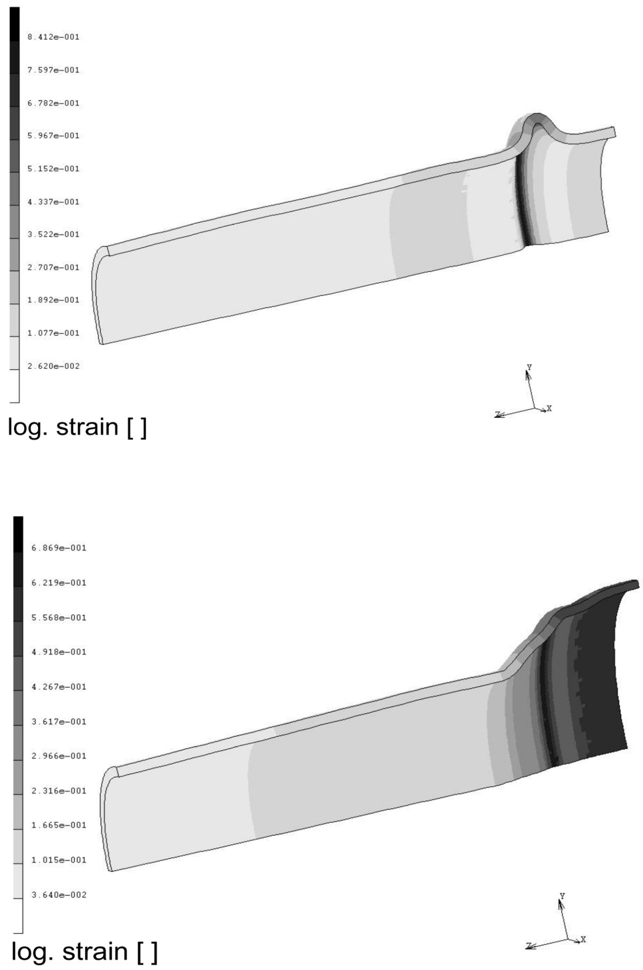

Figure 12. Result of numerical process simulation, using material data extrapolated from compression tests. Top: intermediate state, 30 bar internal pressure; bottom: final state, 40 bar internal pressure.

Bild 12. Ergebnis einer numerischen Prozesssimulation mit Materialdaten aus extrapolierten Stauchversuchen. Oben: Zwischenzustand, 30 bar Innendruck; Unten: Endzustand, 40 bar Innendruck.

The accomplished comparison confirms the necessity of material data determination by procedures possessing a fair similarity to the regarded process.

5 Conclusions

For modeling the material behavior in numerical simulations it is beneficial to use analytical relations. A couple of equations are available for describing the material behavior in the hot temperature range. These equations estimate the flow curve by a combination of the parameters strain, strain rate and temperature as well as factors which have to be adapted to reach an optimal approximation. Regarding material data of tubes made from the aluminum alloy AlMgSi0.5, determined by the recently introduced technology of hot tube bulge tests, the constitutive equation proposed by Hensel and Spittel (1978) shows a very close agreement with the experimental flow data. This is indicated by a stability index of $R^2 = 0.97$. This equation allows for a precise simulative prediction of hot hydroforming processes, when it is fitted to hot tube bulge test data. A comparison of the FE-prediction with the result of an exemplary hot hydroforming process concerning wall thickness distribution of the formed part shows deviations of 5.3% in average. A comparison between material data determined by means of hot tube bulge tests and compression tests, extrapolated to the hot temperature range, shows huge deviations, confirming the benefit of conducting hot tube bulge tests for the determination of material data, when hot hydroforming processes are to be simulated.

Acknowledgments

The authors express their thanks to the DFG (Deutsche Forschungsgemeinschaft) for the support of the project Untersuchung des Werkstoffverhaltens bei der Warm-Innenhochdruck-Umformung (GR 1818/34-1). The achievements described in this paper mainly result from this project.

The scientific results presented in this paper are part of the dissertation of Elsenheimer (2010).

6 References

[1] P. Bortot, E. Ceretti, C. Giardini, *Journal of Materials Processing Technology* **2008**, *203*, Issues 1–3, 381.

[2] G. von Breitenbach, Methode zur Analyse, Bewertung und Optimierung der Prozesskette Profilieren längsnahtgeschweißter Rohre für das Innenhochdruck-Umformen. Dissertation TU Darmstadt, **2007** (in German), Shaker Verlag, Herzogenrath.

[3] E. Doege, Meyer, H. Nolkemper, I. Saeed, Fließkurvenatlas metallischer Werkstoffe. Hanser Verlag, München Wien, **1986** (in German).

[4] J. Dörr, Halbwarm-Innenhochdruck-Umformung von Leichtmetallrohren. Dissertation TU Darmstadt, **2006** (In German), Shaker Verlag, Herzogenrath.

[5] D. Elsenheimer, P. Groche, Determination of Material Properties for Hot Hydroforming, *Prod. Eng. Res. Devel.* **2009**, *3*, 165.

[6] D. Elsenheimer, Entwicklung eines Verfahrens zur Untersuchung des Halbzeug- und Materialverhaltens bei der Warm-Innenhochdruck-Umformung. Dissertation TU Darmstadt, **2010** (In German), Shaker Verlag, Herzogenrath.

[7] P. Groche, G. von Breitenbach, R. Steinheimer, *Steel Research int.* **2005**, *76*, 2/3.

[8] P. Groche, R. Huber, J. Dörr, D. Schmoeckel, *CIRP Annals – Manufacturing Technology* **2002**, *51, Issue 1, 215.*

[9] C. Heller, Umformen von Aluminiumblechen bei erhöhten Temperaturen. Dissertation TU Darmstadt, **1992** (in German), Shaker Verlag, Herzogenrath.

[10] A. Hensel, T. Spittel, Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren. VEB Deutscher Verlag für Grundstoffindustrie, Leipzig, **1978** (in German).

[11] C. Hielscher, Entwicklung eines Halbzeugprüfverfahrens für das Innenhochdruck-Umformen von Hohlprofilen, Dissertation TU Darmstadt, **2000** (in German), Shaker Verlag, Herzogenrath.

[12] S. Kaya, T. Altan, P. Groche, C. Klöpsch, *International Journal of Machine Tools & Manufacture* **2008**, *48*, 550.

[13] M. Liewald, J. Kappes, In-Prozess-Messung beim pneumatischen Warmtiefungsversuch. wt Werkstatttechnik online. Düsseldorf: Springer–VDI-Verlag, 10/**2009**, 753–760 (in German).

[14] L. W. Meyer, A. Weise, F. Hahn, *Journal de Physique IV France* August **1997**, *7/C3*, C3-13-C3-20.

[15] S. Novotny, M. Geiger, Journal of Materials Processing Technology **2003**, 138, Issues 1–3, 594.

[16] B. Rauscher, M. Gösling, W. Homberg, M. Kleiner, *Steel Research International* **2005**, *76*, 925.

[17] A. Yingyot, et al., Warm Forming Magnesium, Aluminum Tubes. Tube and Pipe Journal, September **2006.**

Received in final form: March 25th 2011 T 720