Modelling of size-effects in bulk metal forming processes

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As a result of high tool costs, the design of bulk metal forming processes is often based on experiments with reduced-scale models. By using measured model values the similarity theory allows the calculation of real process factors.
In order to decrease the number of experiments and reduce costs, the metal forming industry uses the Finite-Element Analysis (FEA) for process design and optimisation. Due to the implemented size-independent material characteristics and process parameters, current FEA-software do not take size-effects into account.
The intention of this project is the identification of size-effects in bulk metal forming processes using experimental and numerical investigations. Based on cylinder upsetting and ring compression tests, simulation-relevant characteristic values (e.g. yield curves and friction conditions) are examined in terms of size-effects. Interrelations are derived. A size-dependent friction model is developed with the help of the Numerical Identification method. In the second half of the first project term the resulting conclusions are implemented into the simulation of a complex axisymmetric component, and computations for different volumes of the regarded geometry are accomplished. Simultaneously, experimental trials serve for the verification of the theoretical and numerical results.
The obtained results will improve the FE-simulation of reduced-scale model experiments by the consideration of size-effects.

1 Introduction

In both research and industrial manufacturing, the finite element analysis has become an essential tool for planning, analysis and optimisation of bulk metal forming processes. However, the results obtained by numerical simulations have to be verified experimentally. Trials run on a production line involve high tool costs and result in downtimes. For this reason, the experimental investigations are often performed in reduced-scale test models [1]. Real process variables are calculated from measured model values using the similarity theory, **Fig. 1**.

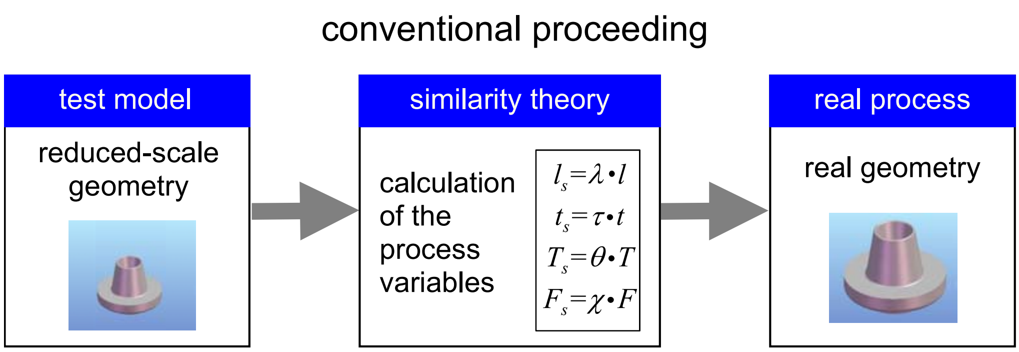

Fig. 1: Design of bulk metal forming processes using the similarity theory

Current commercial FEA-systems for bulk metal forming processes do not take size-effects into account. The simulation model is defined by the selected system of units, meaning that computation results are identical as long as the relationship of the lengths and the size-independent material indices are constant.

For the transfer of test results on other orders of magnitude, the similarity theory is used. The mechanical, dynamic and thermal similarity of two processes is characterised by four constant scale factors which define the ratio between the reduced-scale test model and the real process. In [2] the scale of length λ, the scale of duration τ, the scale of force χ and the scale of temperature θ were introduced as basic scale factors.

Real geometry = scaling factor · model test

$$l_S = \lambda \cdot l \qquad (1)$$

$$t_S = \tau \cdot t \qquad (2)$$

$$F_S = \chi \cdot F \qquad (3)$$

$$T_S = \theta \cdot T \qquad (4)$$

with: l: lenght; t: time; F: force; T: temperature.

Yield curves serve as basic input parameter for the characterisation of material properties in the simulation of forming processes. The yield curve represents the connection between the yield stress k_f and the strain φ_h, depending on the temperature and the strain rate. For the determination of yield curves, the cylinder upsetting test is used. **Fig. 2** shows the schematic description of a plastometer test rig that allows the deformation of a cylindrical specimen with constant strain rate using a logarithmic cam disc.

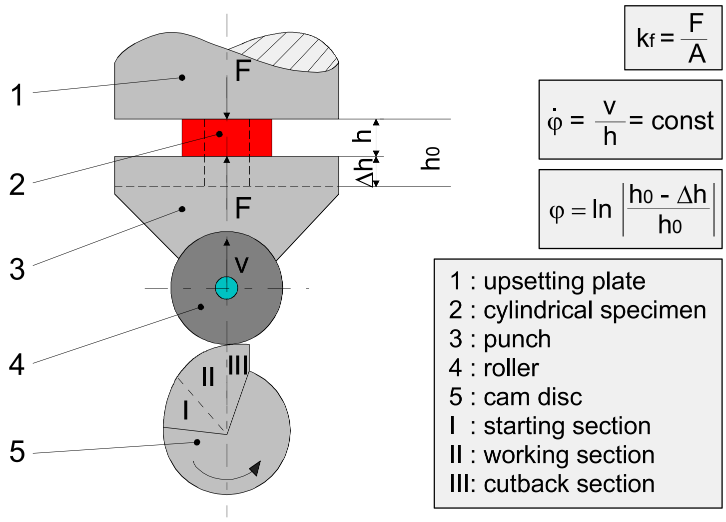

Fig. 2: Schematic description of the plastometer test rig

During the compression, the forming force and the forming distance are measured by means of strain gauges and an inductive position encoder [3]. The yield curves are determined from these measured values for each tested strain rate and workpiece temperature.

Another important variable in the simulation of forming processes is the friction factor m, which describes the relationship between the friction shear stress τ_R and the shear yield stress k_f of the material. For the experimental determination of the friction factor in bulk metal forming processes, the ring upsetting test is used. In this test arrangement, circular specimens are compressed between coplanar upsetting plates under dry friction conditions or with the use of lubricants, as necessary, **Fig 3**.

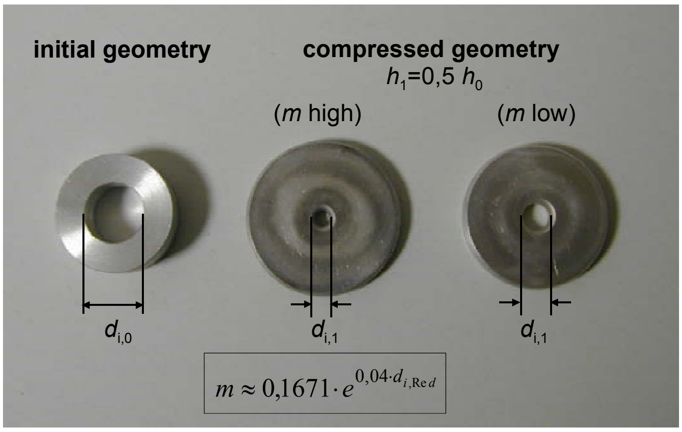

Fig. 3: Ring upsetting test for the identification of friction coefficients in bulk metal forming processes

The change of the inner diameter is associated with the occuring friction during the compression and represents therefore a significant variable for the evaluation of the specimens. The friction factor *m* can be determined by calibration curves alone [4] from the change of the geometrical dimensions of the compressed ring. At a height reduction of 50%, the friction coefficient is calculated according to [5]:

$$m \approx 0.1671 \cdot e^{0.04 \cdot d_{i,\mathrm{Red}}}$$

$d_{i,\,Red}$: reduced inner diameter after the compression

The mentioned deficiencies in simulation of bulk metal forming processes call for improvements of current FE- software packages. **Fig 4.** gives an overview of the intended procedure.

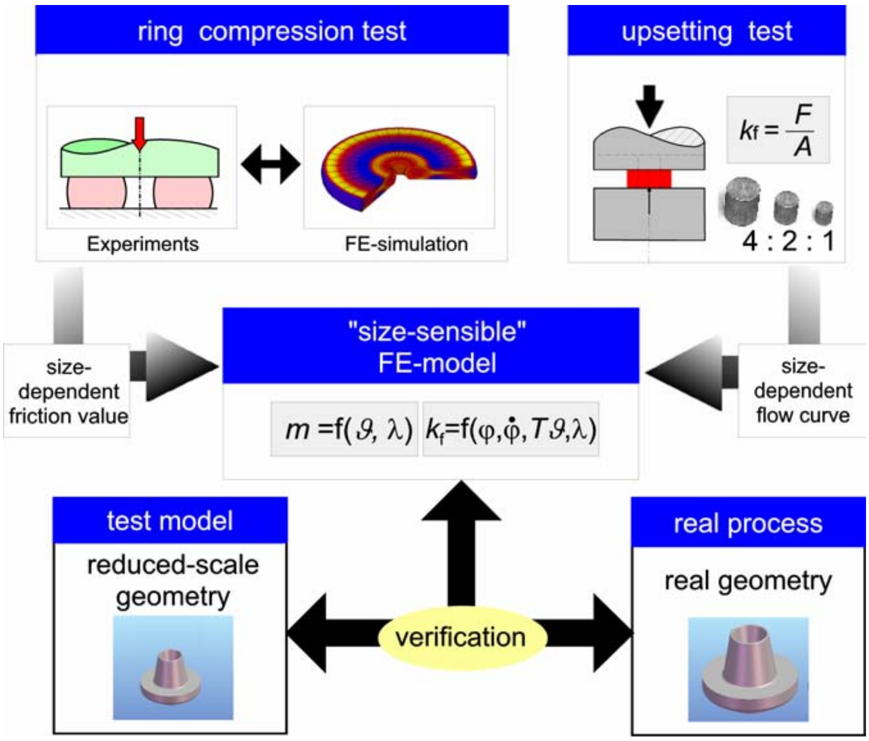

Fig. 4: Development and verification of a “size-sensible” FE-simulation model

The enhancement of the FE-simulation by considering size-dependent yield curves and size-dependent friction conditions requires an experimental quantification of the mentioned size-effects first. Based on the experimental results, connections and principles will be identified and integrated into the utilised FE-software by programming of user-defined subroutines.

2 Experimental Investigations

In order to exclude the reciprocal thermal effects between the test specimen and the forming tools as influencing factor, the magnesium wrought alloy AZ31 is used for the experimental tests in the first project term. Forming temperatures of 250°C-450°C permit the heating of the forming tools so that the forming process is almost isothermal without significant cooling of the workpiece.

2.1 Cylinder Upsetting Tests

The cylinder upsetting tests are carried out at workpiece and tool temperatures of T=350°C, 400°C and 450°C. Furthermore two different strain rates (1 1/s and 10 1/s) are considered. In each case, three specimen sizes with a volume ratio of 4:2:1 and a constant ratio of diameter and height are deformed, **Fig. 5**.

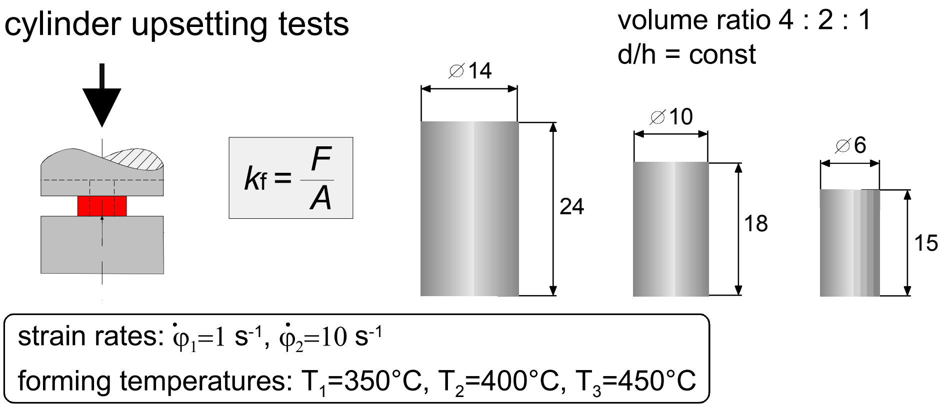

Fig. 5: Upsetting tests of three different specimen sizes. Forming temperatures and strain rates are varied

Fig. 6 shows the homogeneously deformed test specimens at T=450°C for both deformation rates.

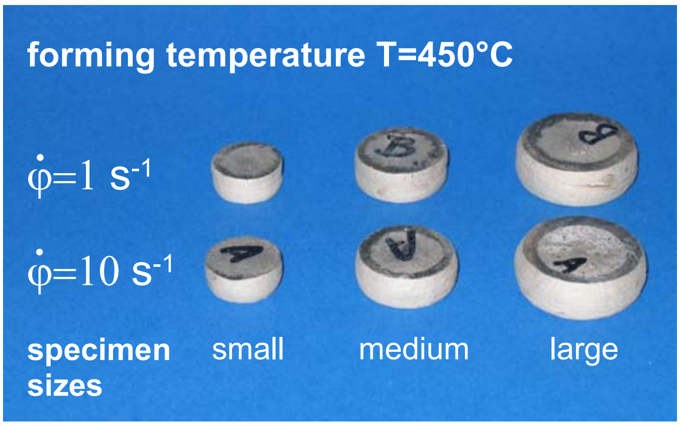

Fig. 6: Illustration of homogenously compressed specimen at 450°C forming temperature

The determined arrays of yield curves show significant differences, that can be ascribed to size-effects on the yield stress. As an example, **Fig. 7** shows yield curves of different specimen sizes determined at forming temperatures of T=400°C and 450°C, strain rate is 1 s^{-1}.

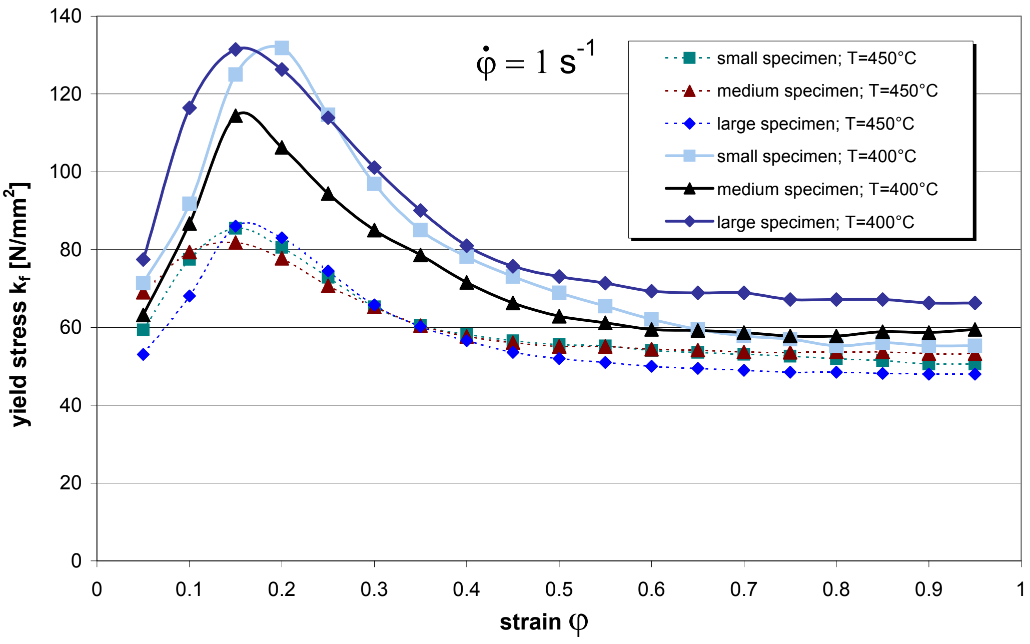

Fig. 7: Arrays of determined yield curves at T=400°C and T=450°C; $\dot{\varphi} = 1\ s^{-1}$

Since several specimens show an inhomogeneous deformation due to inaccuracies of the plane parallelism of the upsetting plates, an assured definition of a principle in terms of size effects on the yield stress is difficult. To obtain improved results some experiments have to be retried. Furthermore the so far processed test range will be expanded.

2.2 Ring Compression Tests

The ring compression tests are also carried out for three specimen sizes with a volume ratio of 4:2:1 at a constant ratio of diameter and height, **Fig. 8**. Forming temperatures of T=350°C, 400°C and 450°C are analysed at dry friction conditions.

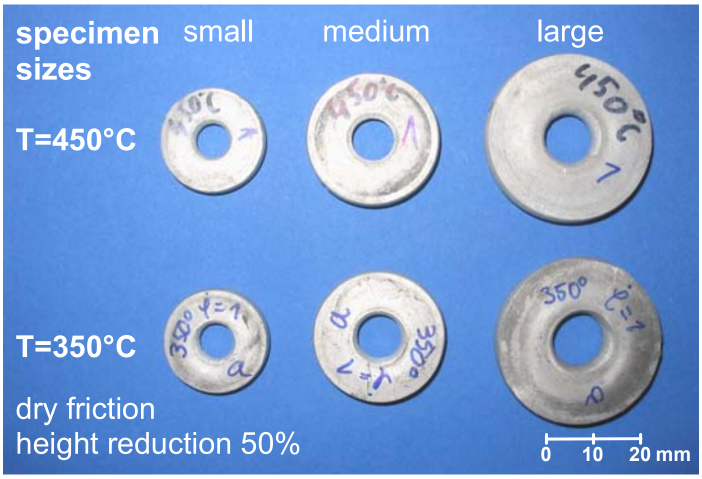

Fig. 8: Illustration of upset ring specimens at forming temperatures of 350°C and 450°C

On the basis of a geometrical analysis of the deformed specimens, the friction factor *m* is calculated for each ring size and temperature condition. In addition to the resulting friction factors, the scales of length λ_i and the different forming temperatures serve as input data for an analysis with the statistical software package STATISTICA®. For the analysed conditions, the functional interrelation of *m* against λ and *T* is described by a regression polynomial of 2nd order. The regression coefficients a_i, b_i, c_i and *d* are calculated with the statistical software.

$$m(\lambda, \vartheta) = a_1\lambda^2 + a_2T^2 + b_1\lambda + b_2T + c\lambda T + d$$
$$a_1 = 0.580281$$
$$a_2 = 0.000008$$
$$b_1 = -0.005088$$
$$b_2 = -0.003641$$
$$c = -0.001620$$
$$d = 1.028728$$

Interactions between the factors λ and *T* are considered in this formulation that is limited to the processed test range. Fig. 9 shows a contour plot that illustrates the functional interrelations.

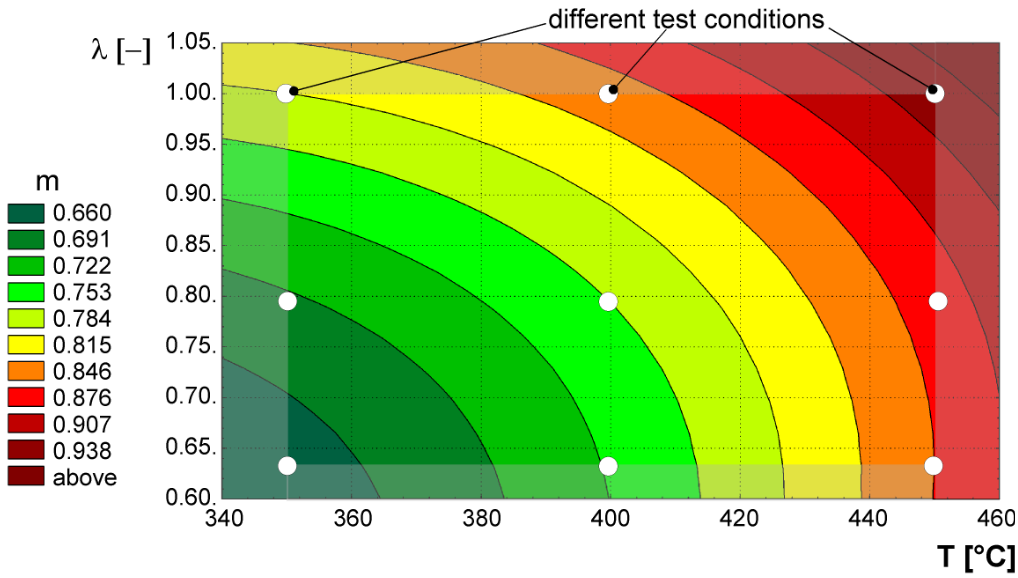

Fig. 9: Graphical representation of the functional interrelation of the friction coefficient *m* against the scale of length λ and temperature *T*

The forming temperature has a significant influence on the friction factor especially in dry friction conditions, as a result of adhesion effects when forming magnesium alloys. For this reason potential size effects can be superposed. To obtain more exact predictions concerning size-effects on the friction factor additional ring compression tests under appropriate lubrication conditions are essential.

3 Numerical Investigations

The simulations are performed with the FE-software package MSC.SuperForm2002 which is optimised for the analysis of bulk metal forming processes. This software features an extensive programming interface which enables the user to integrate own subroutines.
The analysis of the ring upsetting test is realised with an axisymmetric, thermal-mechanical coupled FE-model, **Fig. 10**.

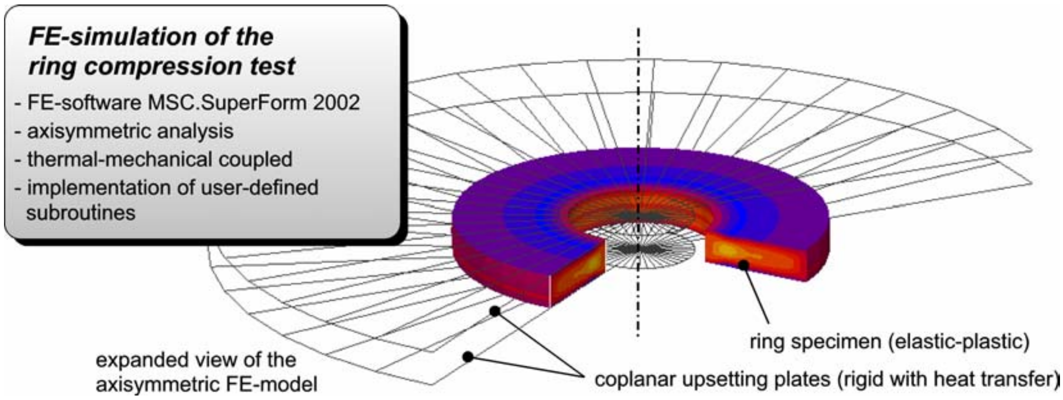

Fig. 10: FE-Model of the ring compression test

The mechanical behaviour of the ring specimen is described by an elastic-plastic material law, whereas the upsetting plates are assumed to be rigid. All relevant process stages are considered in the FE-models including the workpiece cooling. Simulation models are prepared for each experimental test setup. The measured size-dependent yield curves and the identified size-dependency of the friction coefficient will be implemented into the simulation model by means of user defined subroutines.

4 Future prospects

The experimental investigations accomplished so far show significant size-effects on the yield stress and the friction coefficient in bulk metal forming processes. For an accurate quantification of the size-effects further upsetting and ring compression tests are necessary. In order to estimate the size-effects in other dimensions, the processed experimental test range has to be expanded.
After the implementation into the utilised FE-software, the size-dependencies in material properties and friction conditions will be used in the simulation of a complex axisymmetric component. The computations will be verified by experimental trials.

5 References

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