Material Characterization at High Strain Rates with Special Emphasis on Miniaturization and Size Dependencies *

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Abstract

Within the present work the size-dependent flow stress and failure behaviour of various metallic materials is described. Starting with special issues of testing miniaturized specimens, the influence of manufacturing routes and manufacturing induced geometrical deviations is investigated. The specimen size and time-dependent flow stress behavior of C45E, Ti-6-22-22S, and Al7075T6 is presented. The measured behavior is explained by size-dependent friction effects. Additionally, the influence of size and time scaling on the occurring of failure is investigated. A decrease of compressive deformability with increasing size and strain rate was found. The consideration of a size-dependent thermodynamic process character provides a possible explanation for measured size dependencies.

Keywords:

Material, Strain rate, Miniaturization

1 Introduction

The increased miniaturization of components and processes has led to an increased interest in size effects. They may appear as a not directly predictable change of component or process behaviour, even when scaling is done in correct similarity relations. In material characterization size effects under various loading types and conditions are widely discussed (e.g. [1]-[6]). Nevertheless, less is known about size dependencies at high strain rates.

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This study presents experimentally measured size effects on flow stress and failure behavior of different metallic materials within a wide range of strain rates. Special issues of testing miniaturized specimens concerning the influence of manufacturing procedure and geometrical deviations as well as multiple specimen testing are described. Size and time dependencies of flow stress and failure behavior of an unalloyed steel, a titanium, and an aluminum alloy are presented. Possible explanations for the measured behavior result from a size-dependent frictional behavior as well as from size and time dependencies of the thermodynamic state during the deformation process.

2 Special issues of testing miniaturized specimens

2.1 Influence of manufacturing procedure

The characterization of the mechanical behavior of materials starts with the manufacturing of the specimens itself. Especially for testing of miniaturized specimens intensified requirements on accuracy have to be fulfilled.

Preliminary investigations on the influence of different manufacturing routes on the measured material behavior under compressive loading were made by use of the tool steel 40CrMnMo7 [7]. Micro hardness measurements and the determination of residual stresses within the peripheral zone of the specimens lead to different results according to the applied manufacturing procedure, e.g. eroding, grinding, etc. This leads to a significant influence on the measured flow stresses, which were found to be in the order of 50 to 80 MPa. Especially at high strain rates the measured influence of manufacturing routes was increased.

2.2 Influence of geometrical deviations

Due to deviations of guideways and clamping of manufacturing machines as well as oscillations and wear of tools respectively, specimens used in mechanical testing may be flawed by geometrical deviations and roughness of the surface areas. Until now, less is known about the influence of manufacturing induced deviations on the measured material behavior, especially at high loading rates.

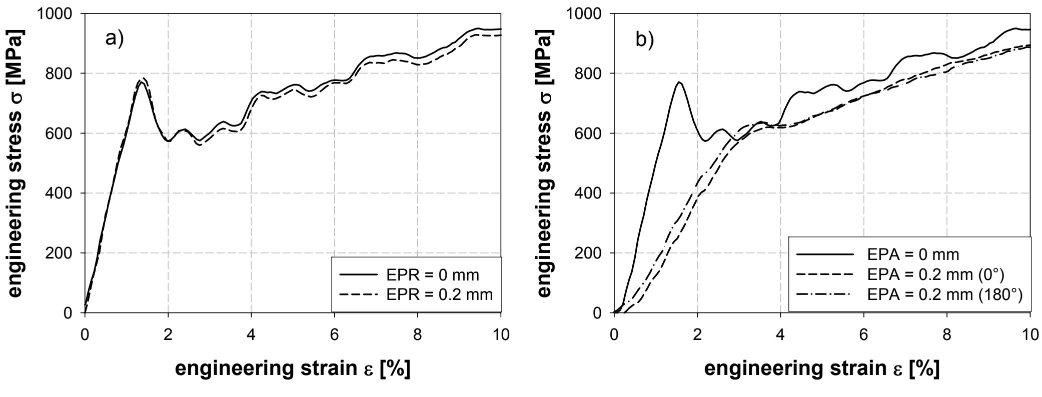

Figure 1: *Influence of (a) rectangularity (EPR) and (b) parallelism (EPA) on flow stress of C45E at 200* s^{-1} *under compressive loading*

Preliminary investigations by use of artificially flawed specimens under compressive loading have shown that e.g. parallelism deviation leads to a distortion of the stress strain distribution and a flattening of the scope in the material`s stress-strain-response (Fig. 1,2). Hence, the true flow stress versus plastic strain is underestimated. Although deviations in rectangularity also distort stress and strain distribution, an influence on the measured flow stresses was not found.

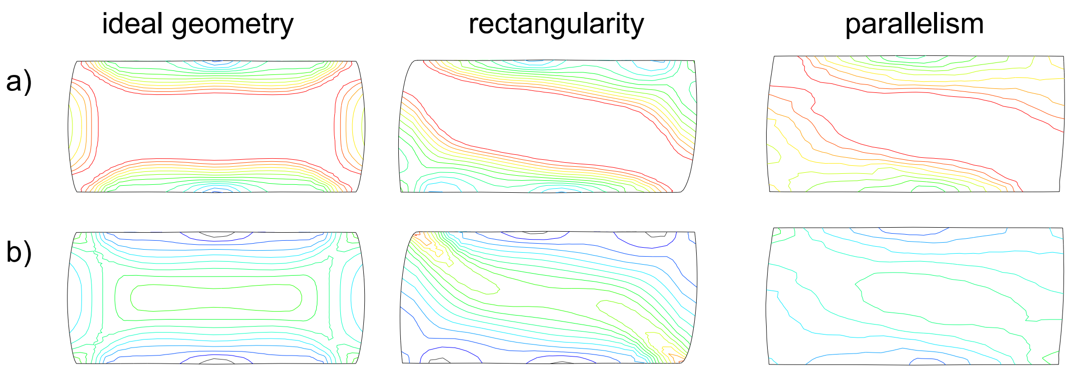

Figure 2: *Distribution of (a) von Mises stress and (b) equivalent strain of geometrically deviated cylindrical compression specimens.*

Under tensile loading conditions geometrical deviations may also influence the measured stress-strain-response of the material. According to the specimen size and type of deviation, a decrease of the macroscopically measured yield stress as well as a displacement of necking to smaller deformations was found by preliminary FEM simulations (Fig. 3).

Therefore, an accurate specimen manufacturing route with smallest geometrical deviations is required for the testing of miniaturized specimens.

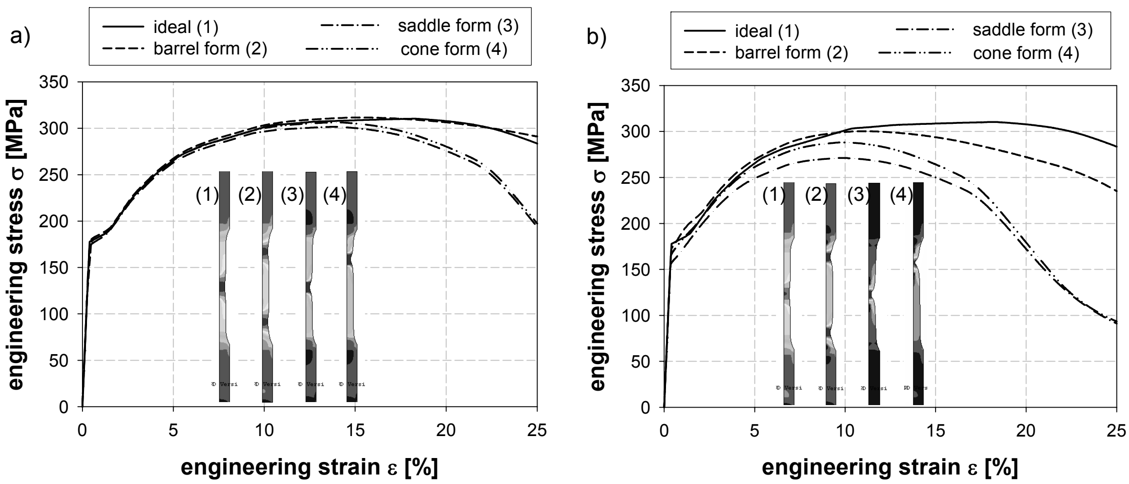

Figure 3: *Influence of geometrical deviations under tensile loading: (a) Ø9x45, (b) Ø2x10 calculated by ABAQUS/Standard*

2.3 Multiple specimen testing

The determination of the flow stress behavior by use of small specimens requires high accuracy and resolution of force and deformation measuring systems. Preliminary studies have shown that multiple specimen testing improves the signal quality by increasing the total measured forces under compressive as well as under tensile loading conditions. The calculated stresses are nearly identical to single specimen tests, but oscillations in force-time characteristics are reduced significantly (Fig. 4a). Hence, multiple specimen testing is appropriate for the determination of the flow stress behavior of miniaturized specimens.

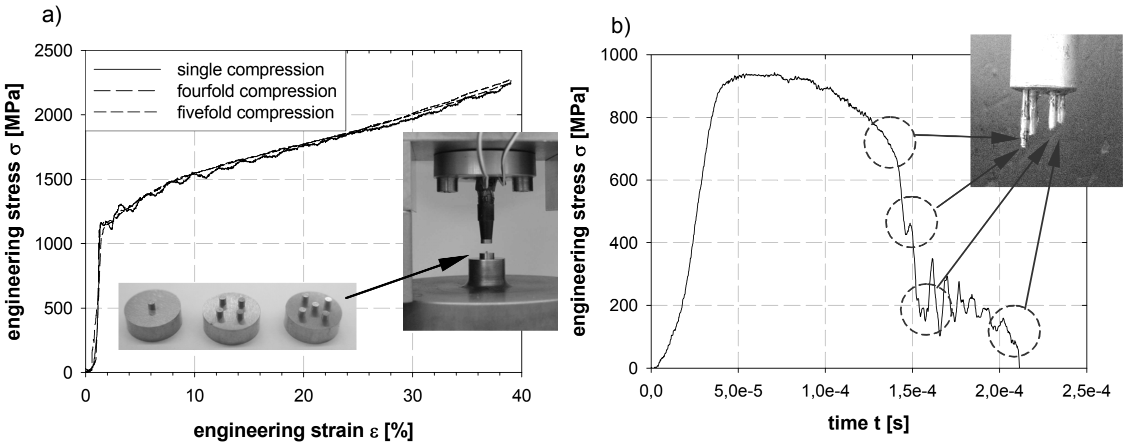

Figure 4: *Multiple specimen testing under high loading rates: (a) cylindrical compression test by drop weight device, (b) tensile test by rotating wheel*

For the investigation of failure behavior of materials single specimen testing is necessary. Due to the statistical character of initiation and development failure occurs at different times and an unequivocal assignment of failure occurring to a definite stress or strain level is not possible (Fig. 4b).

3 Materials and methods

The experimental investigations on size and time dependencies of flow stress and strengthening were carried out by use of the unalloyed carbon steel C45E in a normalized condition. Additionally, an aluminum and a titanium alloy were used for studying size effects on failure behavior under compressive loading. Their chemical composition is shown in Table 1.

For the experimental investigations under compressive loading both commonly available as well as specially designed testing devices were used. The specimens were scaled in diameter between 1 and 9 mm and in aspect ratio (height to diameter) between 0.5 to 1.5, respectively. Under quasistatic and low dynamic loading conditions mechanical and servo hydraulic universal testing machines were applied. Force was measured by calibrated and adjusted load cells. Deformation was measured by strain gauges and incremental gauges respectively.

Carbon steel C45E							
C	Si	Mn	P	S	Cr	Mo	Ni
0.42-0.5	0-0.4	0.5-0.8	0-0.035	0-0.035	0-0.4	0-0.1	0-0.4

Aluminum alloy Al7075 T6									
Zn	Mg	Cu	Fe	Si	Mn	Ti	Cr	Zr	
5.1-6.1	2.1-2.9	1.2-2.0	0.50	0.40	0.30	0.20	0.18-0.28	0.05	
Titanium alloy Ti-6-22-22S									
Al	Sn	Zr	Mo	Cr	Si	Fe	O	N	C
5.75	1.96	1.99	2.15	2.10	0.13	0.04	0.082	0.006	0.009

***Table 1:** Chemical compositions (wt.%)*

High dynamic compression tests at strain rates of 10^2 to 10^4 s^{-1} were carried out by use of drop weight and Hopkinson devices. A detailed description of the test procedure is given in e.g. [8], [9]. In drop weight tests the displacement is measured by incremental gauges. The force is calculated from the elastic deformation of the punch by means of calibrated strain gauges and Hookes law. In Hopkinson tests the stress-strain-response of the material is based on principles of one-dimensional elastic-wave propagation within the pressure bars.

4 Experimental results and discussion

4.1 Flow and strengthening behavior

Fig. 5 shows the size- and time-dependent flow stress and strengthening behavior of C45E, Ti-6-22-22S, and Al7075.

Under quasistatic as well as under dynamic loading conditions a size-dependent flow behavior was measured. The flow stresses of the smaller specimens (Ø1 mm) are significantly higher than those of the larger specimens (Ø9 mm). The differences are about 50 to 100 MPa. Furthermore, Fig. 5 illustrates the dependency of the flow stress from the logarithmic strain rate. The unalloyed steel and the titanium alloy show a thermal activated flow stress behavior. The flow stress is increased with logarithmic strain rate. Their constitutive behavior can be described by the model of Zerilli-Armstrong [10]. For the aluminum alloy a nearly athermal behavior was found. Its constitutive behavior may be described by the model of Johnson-Cook [11].

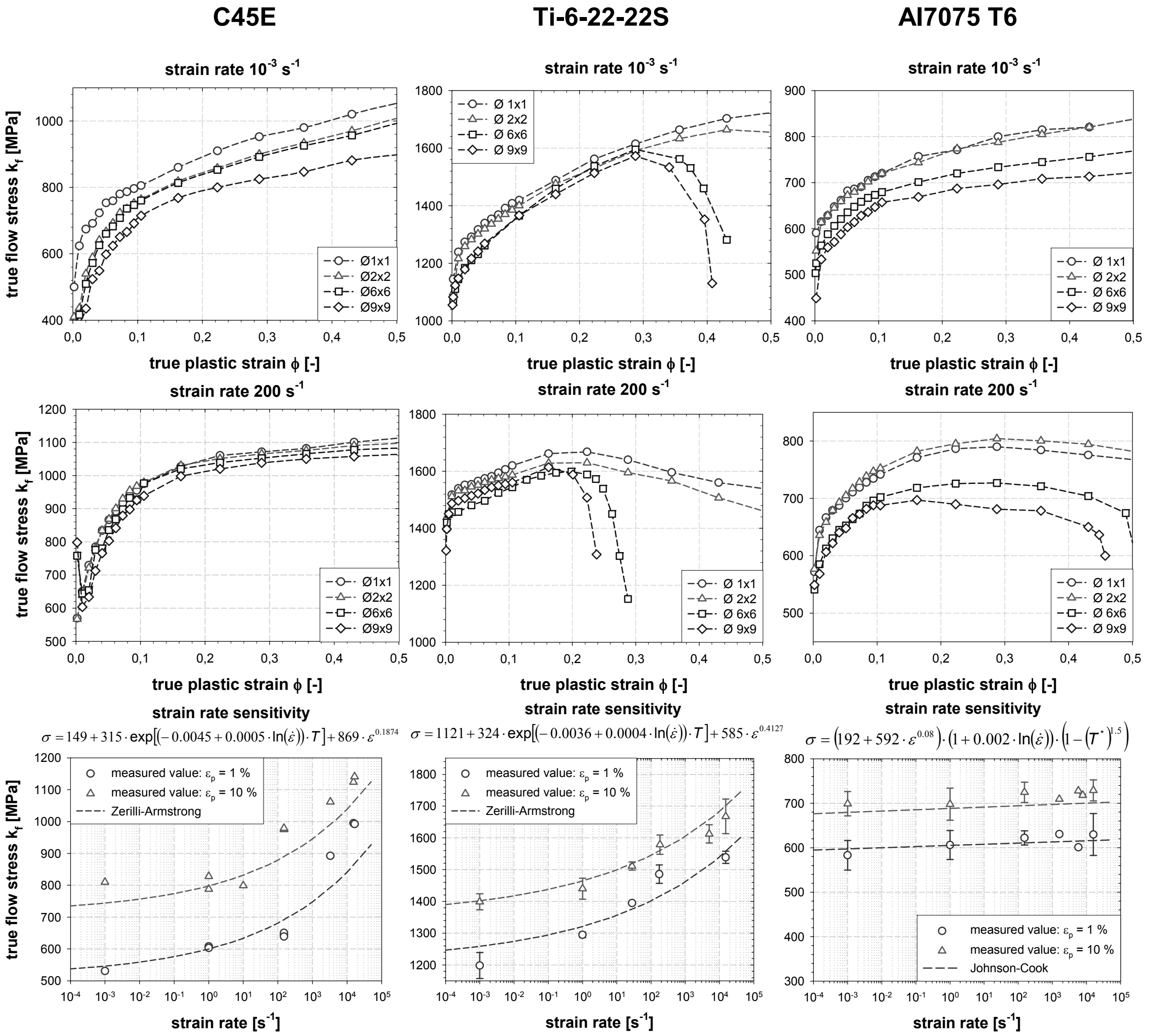

Figure 5: *Size-dependent flow and strengthening behavior of C45E, Ti-6-22-22S, and Al7075 under quasistatic and dynamic loading conditions*

To explain the measured behaviour, the influence of friction on flow stress was investigated. Due to the disproportionate increase of friction-affected surface relative to specimen volume and the fraction of roughness-affected surface respectively, a size-dependent frictional behavior was expected.

To quantify the effect, cylindrical compression tests until 50 % plastic strain were calculated by ABAQUS/Standard and the friction coefficient μ was varied in a range of 0 and 0.15. The deformed geometry was characterized both by ratio of maximum to minimum diameter as well as by the bulging angle α . Furthermore, quasistatic cylindrical compression tests were realized, whereby the deformed specimen was geometrically characterized in the same way. The results are shown in Fig. 6a. Hence, friction-corrected flow curves are calculated (Fig. 6b), which are nearly identical for the different specimen sizes.

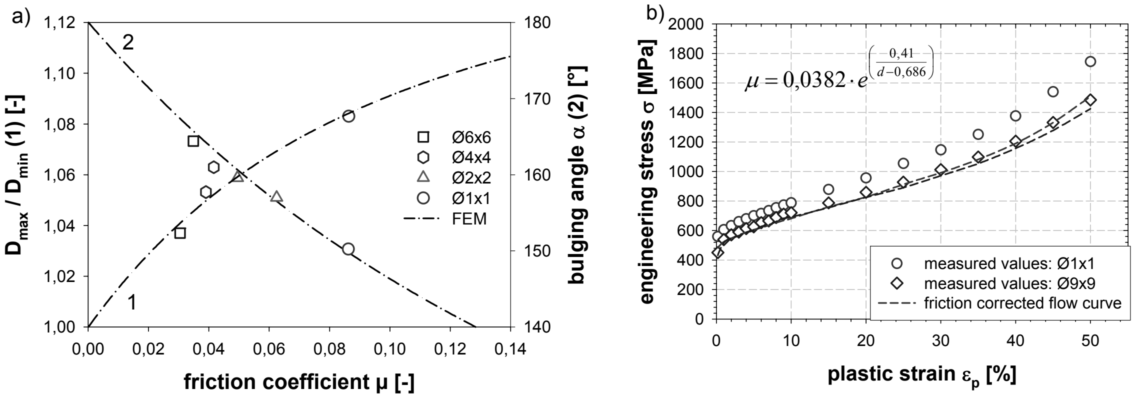

Figure 6: *a) Size dependent friction coefficient μ of Al7075 T6 and b) friction-corrected flow curves of Al7075 T6 at a strain rate of* 10^{-3} s^{-1}

At high strain rates friction may also play an important role. Additionally, the influence of heat development and heat transfer has to be considered.

4.2 Failure behavior

Investigations on the failure behavior of the titanium and the aluminum alloy yield to a significant size-dependent failure initiation and plastic deformability until fracture. There, the titanium alloy tends to fail even under quasistatic loading conditions, whereas the aluminum alloy only failed at high strain rates. Both materials tend to fail due to adiabatic shear bending at high loading rates. Fig. 7 illustrates the size- and time-dependent failure behavior of both materials. An increase of strain rate as well as an increase of specimen size leads to a decrease of compressive deformability.

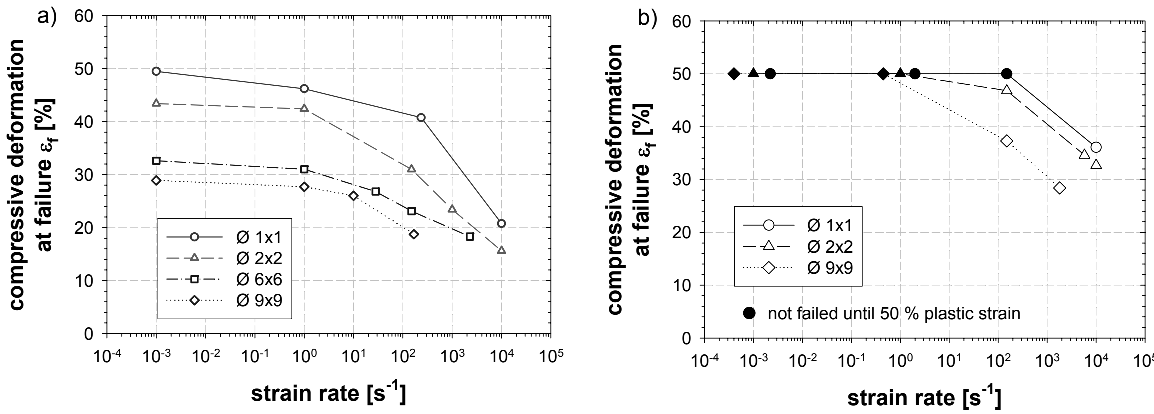

Figure 7: *Size- and time-dependent compressive deformability of a) Ti-6-22-22S and b) Al7075 T6.*

To investigate the failure process itself, stopped cylindrical compression tests followed by microstructure investigations were performed. Hence, a size dependency was found at the microscopic level (failure initiation) and at the macroscopic level (fracture characteristics). Under quasistatic loading conditions the size-dependent failure behaviour is explained by friction effects [12].

At high strain rates thermodynamic aspects are taken into account. In [13], the transition of isothermal to adiabatic process conditions is described by Fourier number F_0 (Eq. 1). The process time t is substituted by strain ε and strain rate $\dot{\varepsilon}$,

$$F_0 = \frac{\alpha \cdot t}{l^2} = \frac{\alpha \cdot \varepsilon}{\dot{\varepsilon} \cdot l^2} \qquad (1)$$

where α is the thermal diffusivity and l the characteristic length.

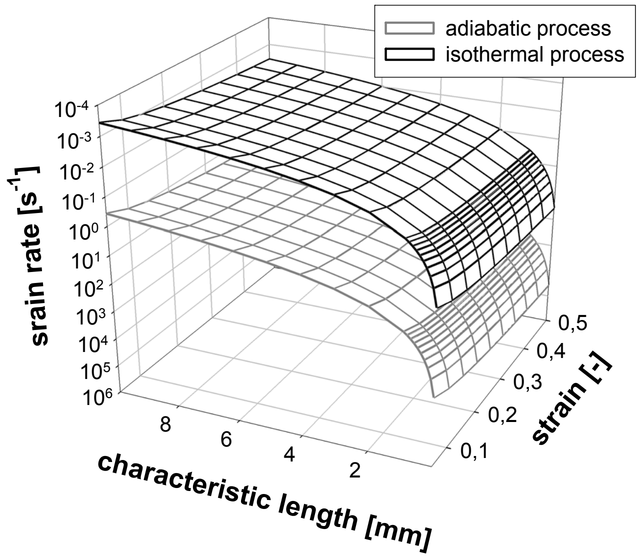

Figure 8: *Size-dependent transition of isothermal to adiabatic process conditions for the titanium alloy Ti-6-22-22S*

Assuming an adiabatic process for F_0 < 0,01 and an isothermal process for F_0 > 10, Fig. 8 can be drawn. It illustrates that the transition to adiabatic process conditions is displaced to high strain rates with decreasing size. Hence, testing miniaturized specimens to obtain highest strain rates would lead to an unknown increase of flow stress due to the minor temperature increase and to an underestimation of temperature-induced softening respectively. However, now the question arises: What happens when the thermodynamic state is kept constant ?

To ensure a constant thermodynamic state represented by Fourier number F_0, the results of stopped cylindrical compression tests for Ø2 mm specimens at 250 s^{-1} and Ø6 mm specimens at 28 s^{-1} were compared. It was shown that both failure initiation as well as compressive deformability were similar (Fig. 9). The larger flow stress of the Ø2 mm specimen is explained by the thermally activated increase of flow stress with increasing strain rate. At loading rates larger than 10^3 s^{-1} this behavior was not confirmed.

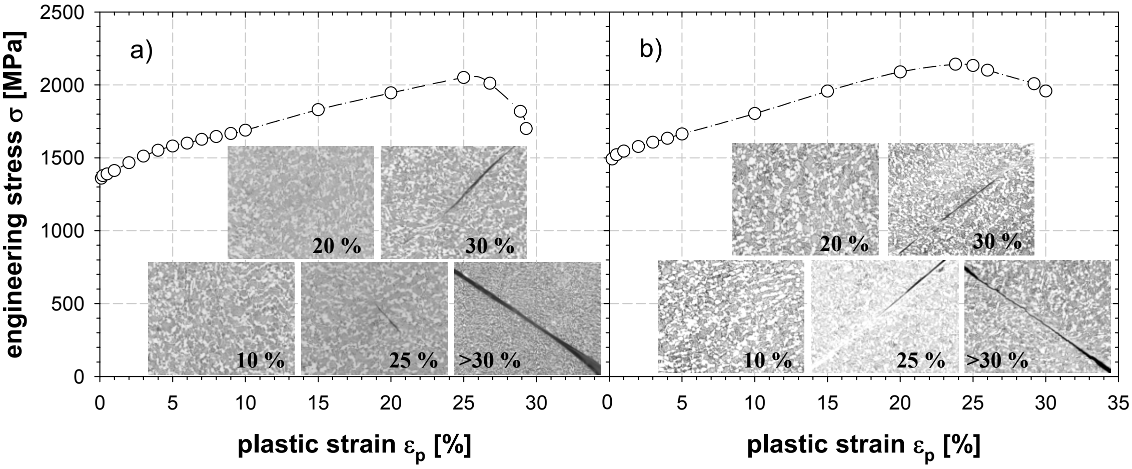

Figure 9: *Failure development for Ti-6-22-22S under compressive loading: a) Ø6x6 at 28 s^{-1} and b) Ø2x2 at 250 s^{-1}.*

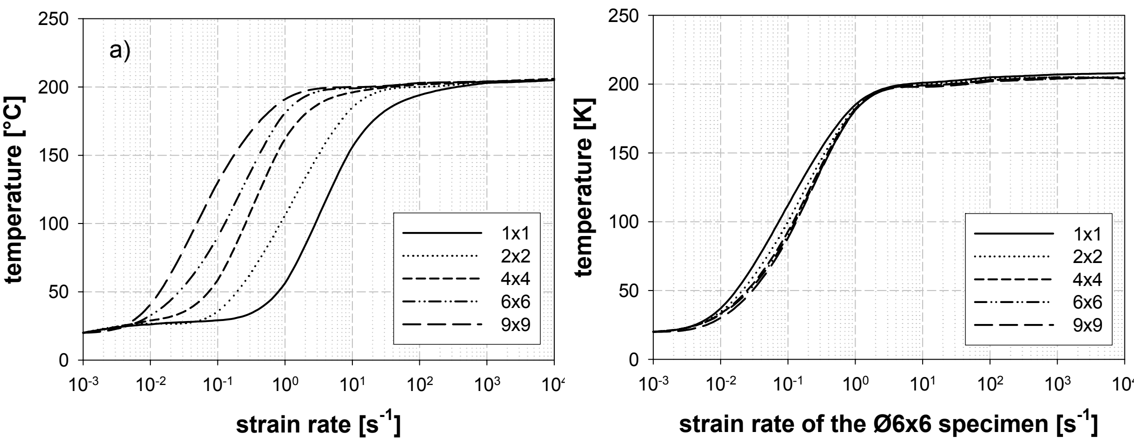

Figure 10: *Size- and time-dependent temperature development in the core of a cylindrical compression specimen (30 % strained) calculated by FEM (Deform 2D): a) without and b) with consideration of the displacement of the transition area from an isothermal to an adiabatic process with reducing size (relating to Ø6x6 specimens)*

The evaluation of the temperature evolution calculated by FEM led to a size-dependent temperature increase versus strain rate (Fig. 10a). Keeping the thermodynamic state constant by adjusting the strain rate relating to Ø6x6 specimens and by applying Eq. 1, a similar temperature development versus strain rate was found (Fig. 10b). This may give an explanation for the measured behavior. At high strain rates (>10^3 s^{-1}) the temperature evolution led to a saturation, which may explain that at highest strain rates the approach described above is not applicable.

5 Conclusions

Within this work it was shown that the mechanical testing of miniaturized specimens leads to increasing requirements resulting from the manufacturing procedure, including the development of micro hardness, residual stresses, and geometrical deviations. A size-and time-dependent flow stress and failure behavior was found for various materials. At quasistatic and low dynamic rates possible explanations are given by increased friction effects with reducing size. Additionally, at high strain rates the thermodynamic state has to be considered. A size- and time-dependent temperature evolution was found, which may cause the macroscopically measured size effect. An adjustment according to Ø6 mm specimens led to a nearly identical behavior. Due to the saturation of temperature development the assumptions made at low and intermediate strain rates up to 10^2 s^{-1} are not directly transferable to describe the material behavior at highest strain rates.

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