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Contact pressure-dependent friction compensation in upsetting tests with miniaturized specimens

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Abstract. Components produced by sheet metal forming can so far only be characterized locally to a limited extent using conventional tests, such as the tensile test or the hydraulic cupping test, due to the size of the specimen. A new approach based on miniaturized upsetting specimens taken from the sheet plane allows to determine the material properties of semi-finished products locally, for example in radii. However, in addition to this specific advantage, challenges such as friction between the specimen and the tool also appear with this testing method. For an accurate determination of the material parameters, it is therefore necessary to correct the test force by the friction coefficient. According to the state of the art, a variety of tests for friction coefficient characterization exist. By using a novel numerical method, friction coefficients for upsetting tests can be calculated contact pressure-dependent by means of an experimental single layer upsetting test. Therefore, in this paper, this method will be used for the first time to compensate the friction part in an upsetting test with miniaturized specimens as a function the contact pressure. This can improve the experimental mapping of the material behavior in the uniaxial compression stress state with increasing strain and hardening, since share of friction force increases with a higher deformation in the upsetting test. In contrast, a friction coefficient compensation based on an average value is provided in order to analyze, whether or in which case a contact pressure-dependent friction compensation is appropriate. In particular, for upsetting tests with miniaturized specimens, these results are relevant, since a major advantage of this test compared to conventional tests besides the local component characterization is the determination of material properties at high strains.

Introduction

The upsetting test with cylindrical specimens is used in bulk metal forming mainly to determine the flow behavior. In this test, a cylindrical specimen is upset between two flat, parallel tool surfaces. Assuming homogeneous deformation, the material behavior in the uniaxial compression stress state can thus be determined, for example, to create material models. The standard for this test is DIN 50106 and, in accordance with this norm, the specimen size may be scaled as required. However, it must be taken into account that size effects can occur in specimens with two dimensions in the submillimeter range [1]. Miniaturized upsetting specimens can be extracted directly from the sheet plane and thus the material behavior of sheet materials in the uniaxial compression stress state can be also characterized [2]. Compared with conventional test methods such as the tensile test, this test method provides the advantages that material properties can be analyzed locally in sheet metal products (dimensions of the specimen < 2 mm) and considerably higher degrees of deformation can be achieved. However, in addition to complicated specimen manufacturing, the test method also faces the challenge of friction influence. During the test, frictional forces occur due to the strain of the cylindrical specimen parallel to the tool surface, which affects the test force. Thus, for a correct calculation of the yield stress, the test force must be compensated to eliminate the friction influence. In forming technology, either the Coulomb friction coefficient model [3] or, for especially high contact pressures, the friction factor model [4] is used to describe the friction behavior. According to [5], the friction coefficient model is valid for friction coefficients to Tresca up to 0.5 or to Mises up to 0.577, if the normal stress σ_N is equal to the yield stress σ. For friction compensation of the test force in the upsetting test, there is the possibility to combine the friction coefficient model and the friction factor model [6]. But usually the Coulomb friction coefficient model is suitable for the upsetting test, because the normal stress in the upsetting test corresponds approximately to the yield stress and the friction coefficients are lower than 0.5 due to the application of lubrication. Consequently, the approach according to Siebel [7], which is based on these model, can be used for friction compensation. Assuming an isotropic deformation of the specimen, the related formula from Siebel allows to calculate the yield stress σ as a function of the specimen diameter d, the specimen height h, the punch force F_P, the specimen area A and the friction coefficient μ:

$$F_P = A \cdot \sigma \cdot \left[1 + \frac{1}{3} \cdot \mu \cdot \frac{d}{h}\right]. \tag{1}$$

Except for the friction coefficient and yield stress to be calculated, all parameters can be obtained by the measured test load and the strain in the loading direction based on the volume constancy under the assumption of homogeneous deformation. Thus, an exact experimental characterization of the friction influence is required to evaluate the yield stress applied in the material of the specimen. Various tests exist for this purpose, such as the strip drawing test or the pin on disk test [8]. But these tests are only suitable to a limited extent for characterizing the friction at high contact pressure or as a function of the contact pressure. In particular, however, it is necessary for upsetting tests, since the contact pressure increases steadily during compression. For example, a tribological system can be modified by the smoothing of lubrication pockets due to an increasing contact pressure. However so far only publications are available that investigated friction compensation with a constant friction coefficient. In this way, Christiansen et al. [6] reduced the friction influence with a numeric approach and Obiko [9] used an analytical approach for that. By means of a new combined numerical-experimental approach according to Kraus et al. [10], the friction can be determined dependent on the contact pressure using a single layer compression test as an improved alternative to the ring test method [11]. This method is adopted in this contribution in order to obtain a non-friction influenced flow curve based on the formula according to Siebel for the upsetting test with miniaturized specimens. Due to the friction compensation, the experimental mapping accuracy of the local material behavior from sheet metal products can be improved. As test material, the conventional deep-drawing steel DC04 with a sheet thickness of 2.0 mm together with the high-strength aluminum alloy AA7075-T6 with a sheet thickness of 1.5 mm are investigated.

Contact pressure-dependent friction coefficient characterization

In order to reduce a flow curve from an upsetting test about the frictional influence, the friction coefficient must first be determined experimentally with a comparable tribological system. The method according to Kraus et al. [10] is based on a single layer upsetting test and therefore excellently suited for characterizing a friction coefficient for an upsetting test. In addition, the method provides the advantage that the coefficient of friction can be evaluated as a function of the contact pressure. The associated methodological procedure is shown in a schematic illustration in Fig. 1. According to that, a single layer compression test must first be carried out experimentally. For this purpose, a round specimen with a diameter of 10 mm is cut from a sheet with the TruLaser Cell 7020 laser (Trumpf GmbH + Co. KG) and subsequently compressed in a tool with two parallel and flat surfaces on the walter + bai testing machine (ZwickRoell AG). A spherical cap in the lower part of the tool ensures parallelism. The specimen is upset by the total strain of $\varepsilon_{TS} = 0.5$ and the nominal strain rate during the test is $\dot{\varepsilon} = 0.005$ 1/s. Three repetition experiments are performed for the two materials DC04 and AA7075-T6. The sample height corresponds to the respective sheet thickness. Both the force and the displacement are measured by the machine throughout the test. Due to the stiffness of the machine, the force and displacement data must be corrected. Therefore a correction curve is generated by closing the upper and lower tool without a specimen, so that the system modulus of the machine and the tool is determined. Using this correction curve, the force and displacement data are corrected accordingly. Since conventional upsetting tests are carried out with a lubricant to reduce friction, the deep-drawing oil Dionol ST V 1725-2 (MKU-Chemie GmbH) is applied before the test. Force-strain curves are calculated for both materials after testing procedure.

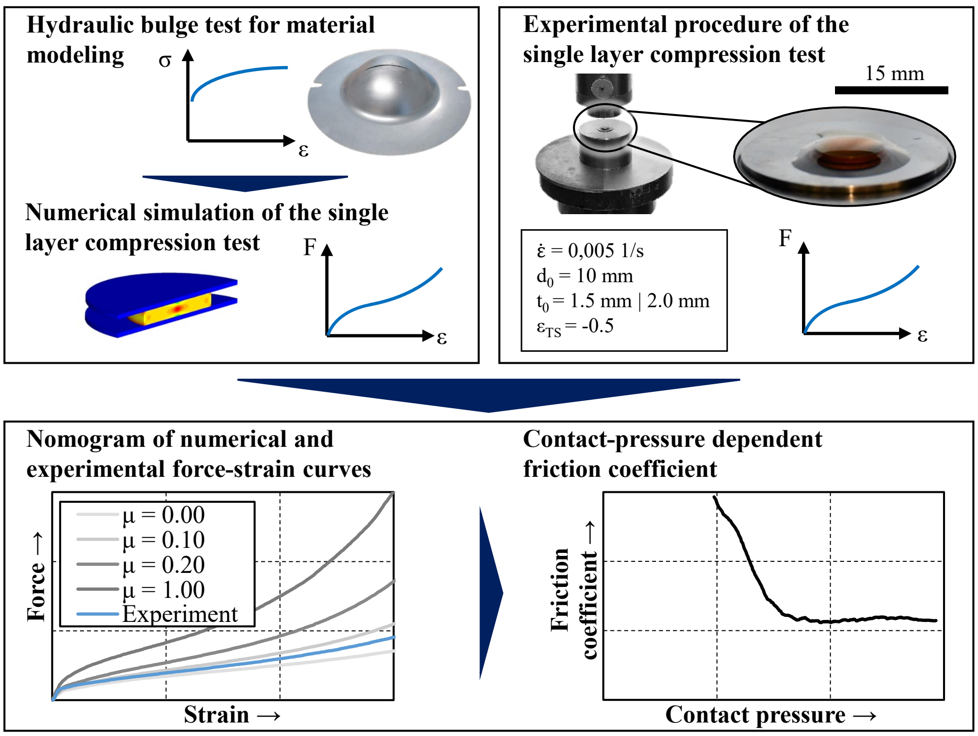

Fig. 1 Method for determining the contact pressure-dependent friction influence according to Kraus et al. [10]

In addition to the experimental performance of the single layer compression test, the experimental setup will also be numerically modeled by the simulation program Ls Dyna (Dynamore GmbH) in order to generate a nomogram for friction coefficient determination. The simulation model is based on the test conditions of the experimental setup. The material model used is Mat_24, which is based on yield locus curve of Mises. The flow curves are extrapolated according to Hocket-Sherby. It is particularly relevant in this method that the deposited flow curve for the material model is not influenced by friction. Furthermore, the yield curve should represent the same stress state as the single layer compression test. In this way, the flow curve from the numerical single layer compression test with a friction coefficient $\mu = 0.0$ is equivalent to the flow curve from the experimental single layer compression test without a friction component. According to Camberg and Tröster [12], the uniaxial compression stress state in the layer compression test with an isotropic deformation is identical to the biaxial tension stress state in the hydraulic bulge test. For that reason, the flow curve from a hydraulic bulge test based on DIN EN ISO 16808 is used to represent the two test materials in the respective simulation model, which is not influenced by friction. Subsequently, the simulation is explicitly calculated for the friction coefficients from $\mu = 0.0$ to $\mu = 1.0$ in the gradations as shown in Fig. 2. The 10 numerical force-strain curves are plotted then with the experimentally determined force-strain curve into a

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nomogram. By interpolation, a friction coefficient can be assigned to each strain value of the experimental force-strain curve. Since the contact pressure in the compression test corresponds approximately to the true stress and each strain value can be assigned to a stress value, the friction coefficient can then be depicted as a function of the contact pressure. It should be noted that the friction factor model is to be preferred if the determined friction coefficient is above 0.5. The respective nomograms for the two materials are shown in Fig. 2.

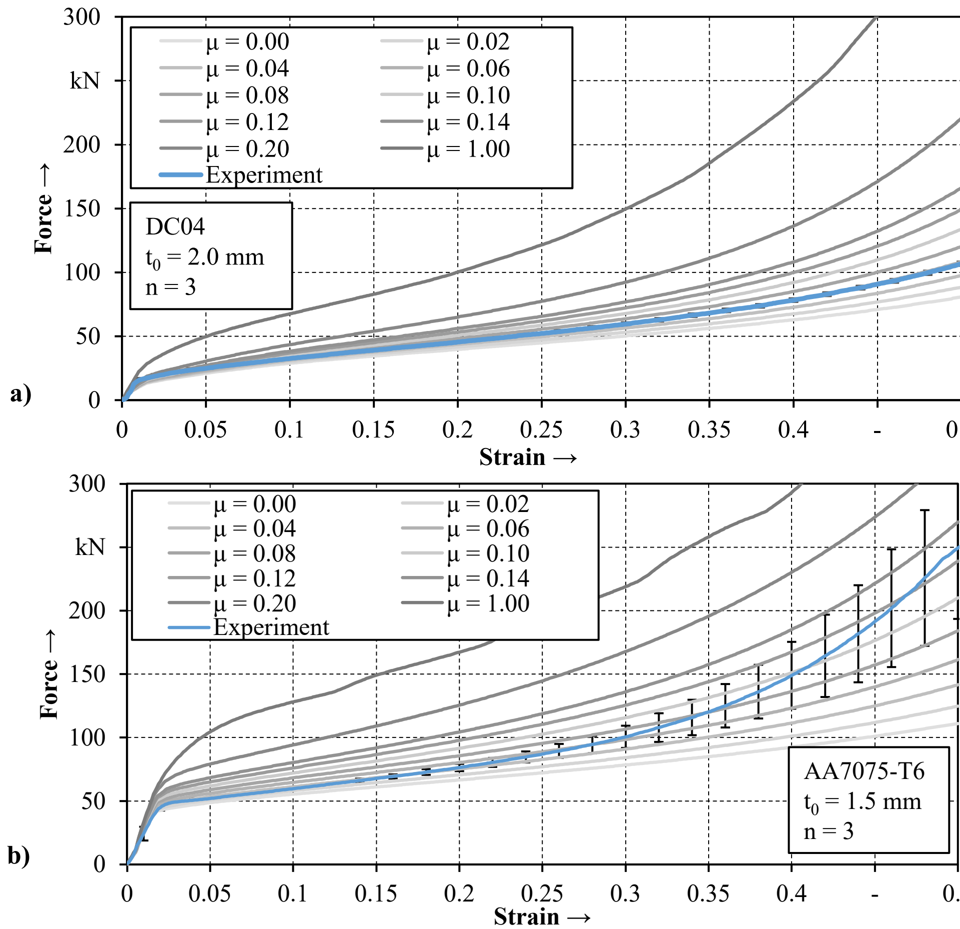

Fig. 2 Nomogram of the numerically determined force-strain curves for different friction coefficients with experimentally measured force-strain curve for the materials DC04 (a) and AA7075-T6 (b)

As expected, the upsetting force increases with higher friction coefficients for both materials. The standard deviation of the experimental force-strain curve is consistently low for DC04. However, for AA7075-T6, the standard deviation increases clearly at a strain of 0.2. After testing procedure, small amounts of the aluminum alloy remained visible on the tool surfaces. Therefore, the higher standard deviation can be attributed to the tendency of aluminum to adhesion. Moreover, adhesion leads to a considerable rise in the force, since the frictional force increases. It should be noted that at low strains, the simulated curves are located close to each other, because in this range the frictional influence is less pronounced. Therefore, it may be necessary to define a limit that determines the range of validity for the specified friction coefficients.

The friction coefficients as a function of strain can subsequently be determined from the nomograms by interpolation. Following Coulomb's friction law [3], the frictional force F_F is a function of the normal force F_N. By extending this formula about the contact area A, the friction stress τ_F can also be described as a function of the contact pressure σ_N and the friction coefficient:

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$$F_F = \mu \cdot F_N \xrightarrow{\cdot A} \tau_F = \mu \cdot \sigma_N \quad (2)$$

Based on the friction law used, the friction influence is dependent on the normal force or contact pressure. Depending on the specimen geometry, for a certain strain there can be different contact pressures. Therefore, the friction coefficient must be shown as a function of the contact pressure and not as a function of the strain.

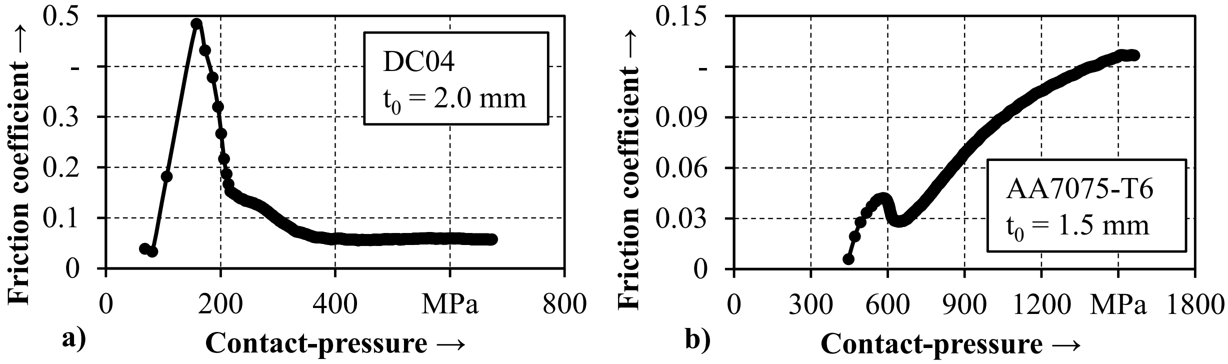

Fig. 3 Contact pressure-dependent friction coefficient for DC04 (a) and AA7075-T6 (b)

By assigning the corresponding true stress from the experimental single layer compression test to the strain, the friction coefficient is obtained in dependence on the contact pressure. In Fig. 3, this functional relationship is shown for DC04 and AA7075-T6. In both diagrams, the curves do not start at a contact pressure of 0 MPa, instead they start at approximately 80 MPa for DC04 as well as at 440 MPa for AA7075-T6. The reason for this is that in this range the experimental force-strain curve is outside the numerically determined curves in the nomogram and thus an interpolation of the friction coefficients is not possible. Initially, the friction coefficient increases for both materials up to a value of 0.48 for DC04 and 0.04 for AA7075-T6. For DC04, thereafter, the friction coefficient decreases continuously with increasing stress, while for AA7075-T6 it increases again at a pressure of 660 MPa. The cause of the increase in friction coefficient is due to adhesion and the resulting raise in friction influence with AA7075-T6. The previous decrease in friction coefficient might be because roughness peaks are smoothed by the increasing contact pressure and thus the friction influence decreases. Since no adhesion occurs for DC04, the friction influence decreases continuously for this material. However, because the friction coefficients for both materials initially increase from the first data point onward with values below 0.01, which are clearly below conventional friction coefficients, it can be assumed that these data points lie outside the previously mentioned range of validity of the nomogram. In this range, the numerically determined force-strain curves have such a close distance to each other in the nomogram that no reasonable determination of the friction coefficient is possible. Therefore, for DC04 the limit for the first valid friction coefficient is set to the maximum at $\mu = 0.48$ at a pressure of 160 MPa, and for AA7075-T6 the limit is set to the first maximum of $\mu = 0.04$ at 590 MPa. By considering a contact pressure-dependent modeling, effects such as adhesion or the smoothing of the surface during the upsetting test are taken into account.

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Friction compensation in the upsetting test with miniaturized specimens

Therefore, the results from the method for contact pressure-dependent friction coefficient determination are now applied to the upsetting test with miniaturized specimens. The procedure for characterization based on Hetz et al. [2] of sheet metal using the miniaturized cylindrical upsetting specimens is shown in Fig. 4. First, sheet metal strips are taken from a sheet by wire electrical discharge machining using the UT2000 (GF machining Solution), from which in turn upsetting samples are separated parallel to the sheet plane by micro electrical discharge machining on the X-200-HPM (Sarix SA). The specimen diameter d_0 corresponds to the respective sheet thickness (DC04 = 2.0 mm, AA7075-T6 = 1.5 mm).

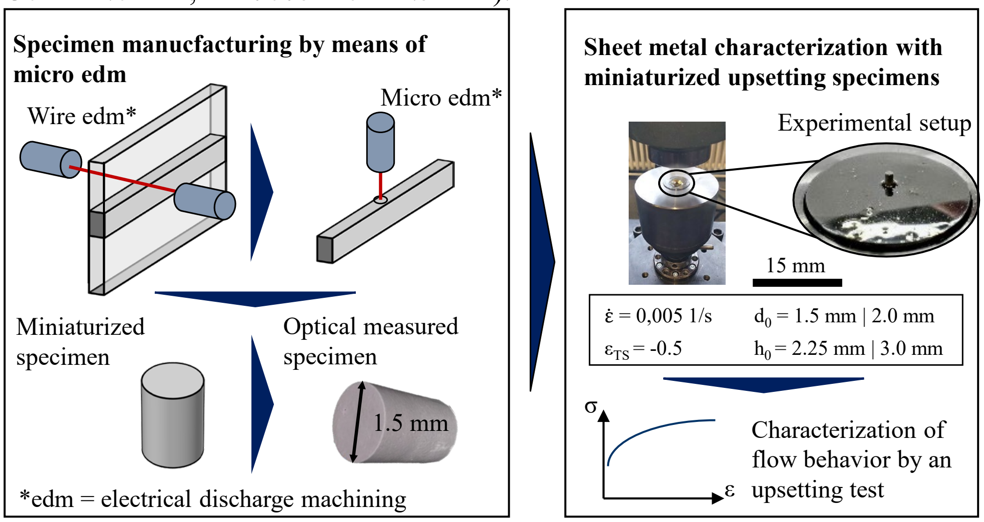

Fig. 4 Methodical procedure for the characterization of sheet metal using the upsetting test with miniaturized specimens according to [2]

Based on a specified upsetting ratio of 1.5, the height h_0 is therefore 3.00 mm for DC04 and 2.25 mm for AA7075-T6. A total of three repetition tests are carried out for each material. All specimens are measured with the Infinite Focus G5 optical measuring system (Alicona GmbH) to ensure dimensional accuracy. After specimen manufacturing, the samples are tested on the Z10 universal testing machine (ZwickRoell AG). The same upsetting tools are used as in the single layer compression test, as well as the same lubricant. Consequently, the tribological system of the upsetting test with miniaturized specimens is comparable to that of the single layer compression test. Also, the specimens are tested by $\varepsilon_{TS} = 0.5$ with a strain rate of 0.005 1/s. The parallelism of the upsetting tools is again ensured by a spherical cap in the lower part of the tool. Both force and displacement data, which are adjusted by a correction cure for the stiffness of the testing machine, are measured. Assuming isotropic deformation, the true cross-section and thus the true stress in the material during the test can be calculated via the volume constancy obtained by the strain in the loading direction. In this way, flow curves are at first created for DC04 and AA7075-T6 without compensation of the friction influence. These curves are shown in Fig. 5. Subsequently, the flow curves are compensated by their friction component according to formula (1) of Siebel. In the two diagrams, the curves are corrected for the respective contact pressure-dependent friction coefficient and for the mean value of the friction coefficients occurring in the respective stress range. Since limits for the validity of the nomogram were previously established, friction coefficients for contact pressures below 160 MPa of DC04 and below 590 MPa of AA7075-T6 are missing. Therefore, the first valid value of $\mu = 0.48$ for DC04 and $\mu = 0.04$ for AA7075-T6 are used for these contact pressure ranges. The mean values of the friction coefficients are $\mu = 0.091$ for DC04 and $\mu = 0.033$ for AA7075-T6.

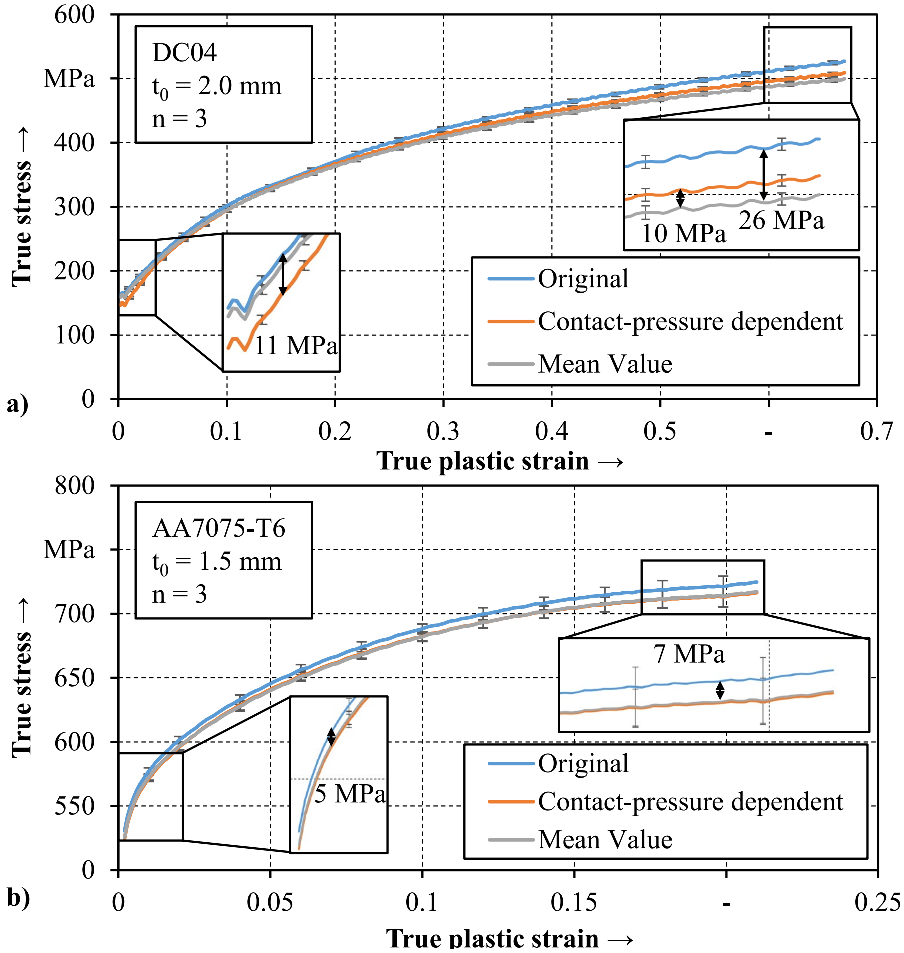

Fig. 5 Flow curves from upsetting test with miniaturized specimens with and without compensation of frictional influence for DC04 (a) and AA7075-T6 (b)

For AA7075-T6, the difference between contact pressure-dependent and mean value compensation is marginal and can be neglected. This is due to the fact that the friction coefficients in the contact pressure range, which is equivalent to the stress range of the flow curve, are quite small and change only slightly compared to the mean value. However, it must be noted that the influence of the friction coefficient would increase substantially at higher contact pressures due to adhesion. But the flow curves of AA7075-T6 are only available up to a contact pressure of 750 MPa, because due to microcracks in the miniaturized upsetting specimen about a true strain of 0.21. In the case of DC04, the contact pressure-dependent friction coefficients deviate clearly from the mean value to a certain extent. Therefore, this leads to distinct differences in the two types of friction compensation used at the yield strength and is increasing with higher strains. The difference is about 10 MPa at the yield strength, which corresponds to about 5 percent of the yield stress at this point. At higher strains, the difference is much smaller with about 2 percent of the yield stress resulting in an absolute value of 10 MPa as well. For both materials, it can be recognized that the share of friction force increases with higher strain. This is due to the fact that a compression of the specimen decreases the height and increases the diameter. It can be conducted in accordance with the formula of Siebel (1), that a reduction in the ratio of height to diameter increases the amount of friction and also leads to a change in surface properties. For this reason, friction influence at high strains should generally be compensated either as a function of contact pressure or independently of contact pressure.

Summary

Consequently, a contact pressure-dependent friction compensation leads to a substantial improvement in the mapping of material behavior in the characterization with upsetting tests. It should be noted that the friction coefficient as a function of contact pressure is clearly dependent on the material and differs significantly from an averaged friction coefficient at the yield strength in the case of DC04. For AA7075-T6, the difference is considerably smaller, but contact pressure-dependent friction compensation is also required here if stresses above 800 MPa are reached. Despite that, a contact pressure-dependent friction coefficient determination for low contact pressures is only possible to a limited extent with presented the method, so there is still a need for research for this case. In conclusion, it is recommended to compensate the friction influence in the upsetting test as a function of contact pressure. In this way, for example, the yield strength of the material in sheet metal formed parts can be measured much better by the upsetting test with miniaturized upsetting specimens, which has a particularly large influence in material models and thus in the numerical imaging accuracy.

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