# Influence of Strain Rate on Biaxial True Stress – True Strain Curves from the Bulge Test

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**Abstract.** The present investigation deals with the determination of biaxial true stress – true strain curves from the hydraulic bulge test. Harmonization and standardization of the bulge test with an optical measurement system, which was worked out at the German IDDRG working group "bulge test" will be shown. Additionally, the paper deals with the investigations on strain rate sensitivity of the DX54 and DP600. Furthermore one possibility to control the strain rate during the test will be shown.

## Introduction

Finite element analysis (FEA) has become indispensable for cost effective product design of sheet metal forming processes [1]. To fully use the potential of FEA, a realistic mathematical description of the material behavior is required. The mathematical models have to be parameterized via experiments. One of the crucial parameter is the true stress - true strain curve which describes the strain hardening of the material.

The accepted and standardized uniaxial tensile test for sheet metal testing [2] enables the strain hardening description. But the test delivers experimental data only up to the uniform elongation. Beyond the point of the uniform elongation, the hardening curve is usually extrapolated for example by the mathematical approaches of Ludwik, Gosh, Hollomon, Hocket-Sherby or Voce. Due to the different mathematical approaches, the extrapolated flow curves show the anticipated different curve shapes (Fig. 1).

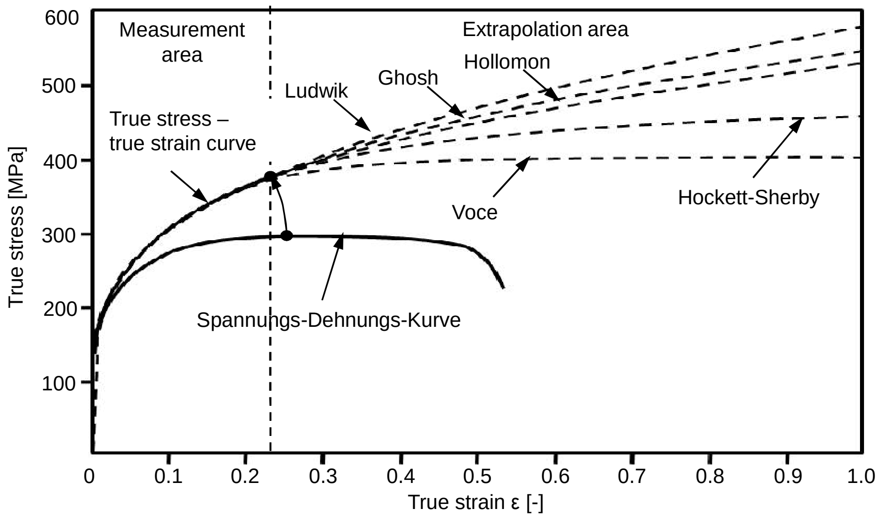


Fig. 1: Example of an extrapolated true stress –true strain curve based on the uniaxial tensile test

A more accurate extrapolation can be achieved with the help of the bulge test, which enables an experimental determination of biaxial true stress - true strain curves at higher strain values [3 - 6]. The determination of the biaxial true stress - true strain curve with optical measurement was worked out at the German IDDRG working group "bulge test" [7]. In the working process of the group the strain rate sensitivity of the mild steel DX54 was proven by using the bulge testing method. Especially strain rates higher than $\dot{\varepsilon} = 0.1\ s^{-1}$ lead to an increase of the stress. So the working group recommended a constant strain rate of $0.05\ s^{-1}$ or a testing time of 2-4 minutes [7].

This paper focuses on the strain rate sensitivity. In addition the influence of the strain rate for the dual-phase steel DP600 will be shown. Furthermore, a method will be presented to influence the strain rate by regulation of the flow rate of the oil of the hydraulic system in compliance with the recommendation of the working group "bulge test".

## Hydraulic bulge test

### Test equipment and procedure

The bulge test at the IFUM is carried out in a modular tool system in a hydraulic press. The tool consists of a blank holder, a die, a fluid chamber and a hydraulic system with a maximum pressure of 400 bars. The bulge diameter can be chosen from 50, 100, 150, 200 and 250 mm. For the following investigations the diameter of 200 mm is used. During the test a circular blank is completely clamped. A bulge is formed by pressing a fluid against the blank until fracture occurs. Furthermore a lock bead in the blank holder is realized to avoid any material flow from the flange area. Additionally the tool is equipped with a measurement system in the middle of the fluid chamber which enables to measure the pressure of the fluid during the test. For the measurement of the curvature radius and the geometrical change of the blank the measuring system ARAMIS [8] is placed above the blank. A typical ARAMIS system consists of the sensor (two cameras and a light source). To protect the measuring system from splashing oil at failure, a glass plate is placed in front of the lenses of the optical measuring system. The calibration of the system was done with inserted protection.

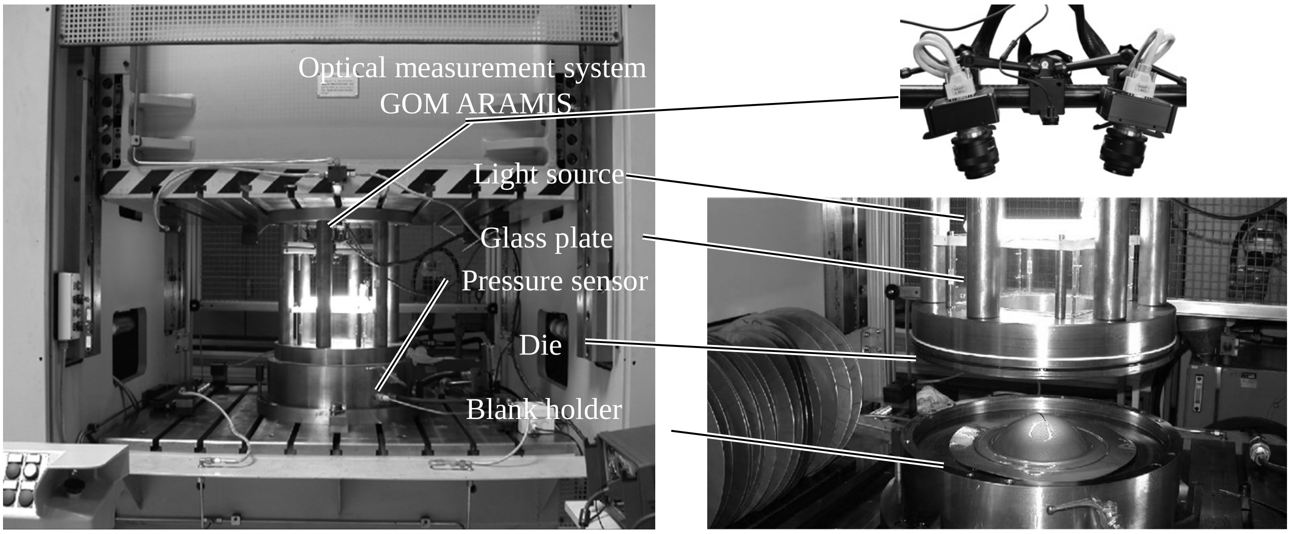


Fig. 2: Modular tool system for the bulge test with an optical measurement system GOM Aramis [9]

To enable the ARAMIS system to measure the geometrical change, a stochastic pattern was applied to the specimen's surface and synchronized stereo images of the pattern were recorded at different loading stages. For example, Fig. 3 shows the undeformed a) and the deformed situation for the specimen b). The undeformed situation represents the initial measurement. This image is divided into a large amount of subsets (facets). Therefore the center of each facet is shown as a cross, five facets are shown as quadrangle. After that the corresponding area is calculated for all loading stages for each face. Based on the measured geometry the ARAMIS system enable the calculation of 3D coordinates, displacements, speeds, surface strain tensor (strain x, -y, xy, major, minor, thinning) and strain rate.

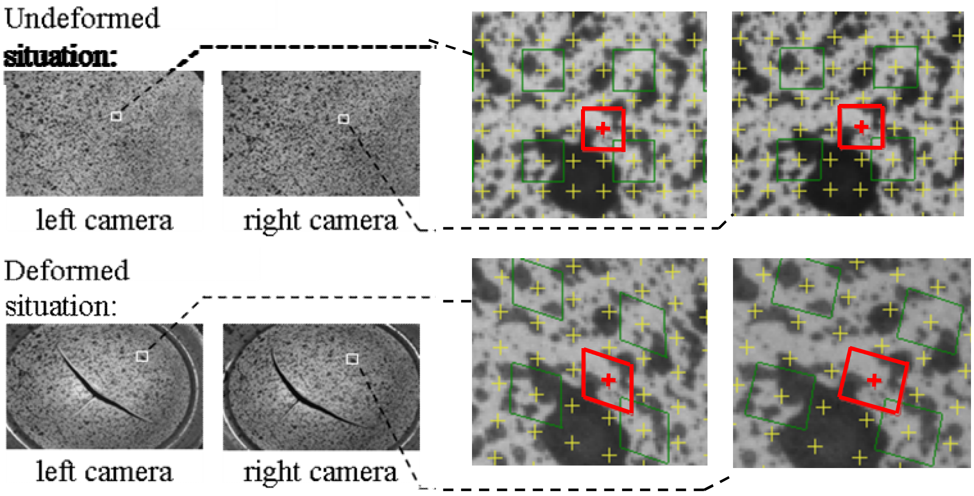


Fig. 3: Left side full image size, right side enlarged local area with mathematical subsets (facets) for the calculation of surface point positions [8, 9].

**Calculation of biaxial true stress - true strain curve**

For the calculation of the biaxial true stress - true strain curve the pressure of the fluid $p$, the radius of curvature $\rho$, the local thickness $t$ and the local strains $\varepsilon$ from the bulge test have to be known. Many investigations [9-10] are done for determination of the biaxial true strain - true stress curve. In the following investigation the recommended spherical fit method of the working group "bulge test" is used. Fig. 4 shows the test principle with the necessary values.

| | | |
|---|---|---|
| $h$ | = | Dome hight |
| $p$ | = | Fluid pressure |
| $\rho$ | = | Radius of the curvature |
| $t_0$ | = | Initial sheet thickness |
| $t$ | = | Actual sheet thickness |
| $\varepsilon_1$ | = | Major strain |
| $\varepsilon_2$ | = | Minor strain |
| $\varepsilon_{eq}$ | = | Equivalent stain at the appex of the dome |
| $\sigma_b$ | = | Bi-axial stress |
| $d_{die}$ | = | Die diameter |

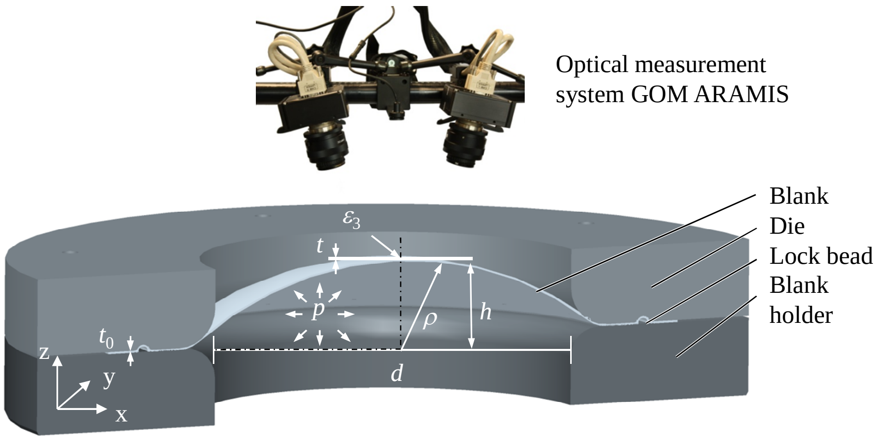


Fig. 4: Test principle bulge test

Following it is possible to determine the corresponding biaxial membrane stress using the equations 1-3 [9]. Because of the constant volume the actual sheet thickness can be calculated by:

$$t = t_0 \cdot \exp^{(-\varepsilon_1 - \varepsilon_2)}. \quad (1)$$

Assuming the membrane stress state of a thin-walled the biaxial true stress can be determined according with:

$$\sigma_b = \left( \frac{p \cdot \rho}{2 \cdot t} \right). \quad (2)$$

Furthermore the thinning strain is calculated by:

$$\varepsilon_3 = -\varepsilon_1 - \varepsilon_2. \quad (3)$$

Many investigations to determine an uniaxial stress strain curve from biaxial true stress - true strain curve was done by Sigvant [11], Kuwabara [12] and Barlat [13].

## Investigation of the strain rate effect

For the determination of the strain rate sensitivity a mild steel DX54 $t_0$ = 1.0 mm and a dual phase steel DP600 $t_0$ = 1.4 mm are investigated. In this study, bulge tests were conducted with different flow rates by using a servo vale of the hydraulic unit. So the servo valve enables the control of the flow rate during process.

Thereby two different flow rates of the hydraulic system A and B and two changing flow rates C and D during the test are analyzed. In Fig. 5 the biaxial true stress - true strain is plotted and the thinning rate of the experiment is plotted over the equivalent strain.

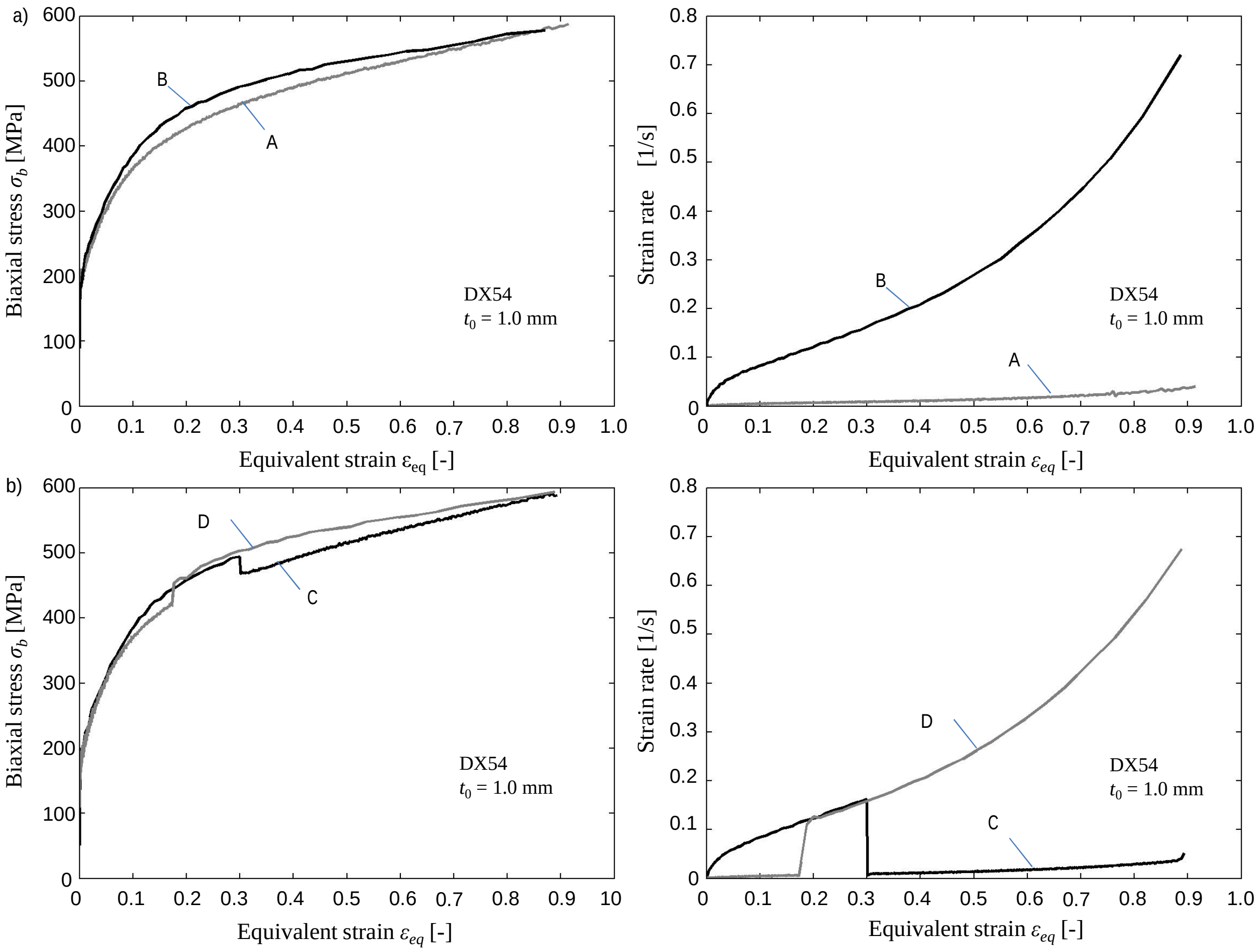


Fig. 5: a) Biaxial stress-strain curve (left) and thinning rate (right) for quasi static curve A and increasing strain rate conditions curve B b) Biaxial stress strain curve for changed strain rate conditions, for curve C the thinning rate switch from a high strain rate to a lower strain rate and curve D switch for a low strain rate to a high strain rate

It can be shown that a higher strain rate results in a higher biaxial stress $\sigma_b$ value. Towards the end of the experiment the curves are turning until they overlap. The conclusion of Volk to take the strain rate sensitivity into account for mild steels [14] can be affirmed. Furthermore in Fig. 5 b) could be shown, that the strain rate sensitivity is independent of the strain rate history. With the increasing sheet thinning the thinning rate increases due to the fact that the flow rate of the oil is constantly rising. If the flow rate of the hydraulic system, or the punch speed in other bulge systems, is too high the thinning rate is increases exponentially. To counter this, a slower flow rate of the oil or slower punch speeds have to be set up

One option to reduce the test time and to control the strain rate is to decrease the flow rate of the oil or the punch speed over the test period.

For the DP600 quasi-static conditions, quasi-static conditions with a decreasing flow rate of the oil and an increasing strain rate are investigated. In Fig. 6 biaxial true stress - true strain is plotted and the thinning rate of the experiment is plotted over the equivalent strain.

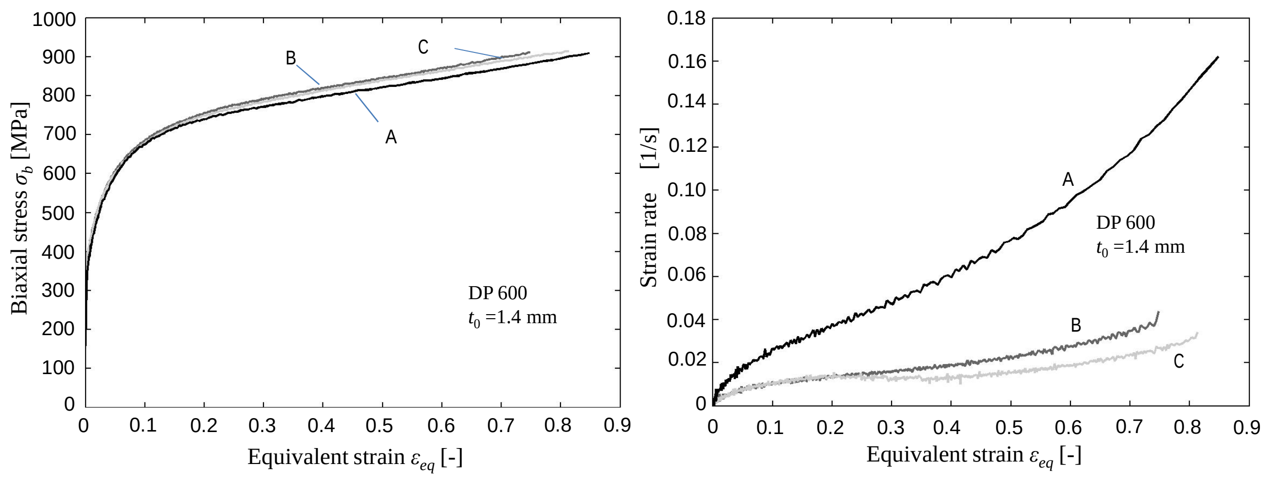


Fig. 6: Biaxial stress-strain curves and thinning rates for quasi static conditions curve C, curve B with a reduced flow rate of the oil during the test and for increasing strain rate curve A

Furthermore it can be shown that a high strain rate result in a minimum lower biaxial stress $\sigma_b$ value of 3%. But the biaxial true stress-true strain curve A shows a steeply sloping in the middle and afterward stepwise rising at the end. The curves which are determined under quasi-static conditions (B and C) show a homogenous strain hardening. Complementary to the work of Volk [14] the strain rate sensitivity of high strength steel has to be taken into account. Moreover the biaxial true stress true strain curve which is determined at quasi-static conditions C and by a reduced flow rate B show no significant deviation. So the reduction of the flow rate or the reduction of the punch speed during the test enables to reduce the testing time by a constant quality of the result.

## Summary

In this paper the strain rate sensitivity of the mild steel DX54 and of the high strength steel DP600 was investigated. The conclusion of Volk to take the strain rate sensitivity into account for mild steels was affirmed and in complementary to the work the strain rate effects for the high strength steel DP600 was presented and have also to be taken in consideration like for mild steels.

Furthermore a method was presented to influence the strain rate by regulation of the flow rate of the oil of the hydraulic system in compliance with the recommendation of the working group. It can be shown that via a flow rate reduction during the process the strain rate can be adjusted still to the point of instable necking. Future investigation will focus on the strain rate control with constant strain rates.

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