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Innovative measurement technique to determine equibiaxial flow curves of sheet metals using a modified Nakajima test

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ABSTRACT

Since an inhomogeneous punch pressure distribution occurs in the Nakajima test, equibiaxial flow curves have been determined solely in the hydraulic bulge test so far. By using an innovative measurement technique, it is possible to determine both the punch pressure and strains that occur in the Nakajima test. In this paper, a calibration and realization strategy is presented that allows to determine accurate equibiaxial flow curves for sheet metal materials using a modified Nakajima test without inverse parameter identification. This setup is suitable to substitute the expensive and time-consuming hydraulic bulge test by a simple and common experimental setup.

1. Introduction

The uniaxial tensile test is a common test for characterizing the material behavior of sheet metals [1]. With this test the stress–strain curve of a sheet metal material can be derived easily with the benefit of a friction-free setup. Nevertheless, there is a crucial drawback of this test: the maximum strains that can be evaluated are usually not larger than 20% for standard steel grades because the uniform elongation ends. However, in real forming processes depending on the used material equivalent strains of 50% ... 100% can occur especially under equibiaxial loading conditions. So it is necessary to extrapolate the test data of the uniaxial tensile test to higher strains. In the state of the art some other tests exist to overcome this problem. The in-plane torsion test is an interesting option to derive experimental based flow curves up to equivalent strains of 150% ... 200%. The challenge for this test is the specimen preparation and the relatively high experimental effort [2]. The hydraulic bulge test is also widely used to generate data at strains above the uniform elongation in the tensile test [3]. This strategy is standardized in Ref. [4]. During the hydraulic bulge test a sheet metal is clamped between a die and a blank holder and loaded by a hydraulic oil under almost friction-free conditions, whereby an equibiaxial loading of the sheet metal results. Utilizing digital image correlation (DIC), the strains can be measured during the test. Using the membrane equation, the equibiaxial stress–strain curve of sheet metals can be determined [5]. The test is typically performed until fracture occurs. One important challenge of the hydraulic bulge test is the increasing strain rate for higher strains. In Ref. [6] a strategy is presented to overcome this problem in combination with a response surface approach. In Ref. [7] improvements for the geometrical description of the bulged sheets are proposed. Nevertheless, the hydraulic bulge test has several disadvantages: the test equipment has to be prepared, the hydraulic oil has to be filled into the reservoir; after that the test equipment has to be cleaned from the hydraulic oil that was splattered because of the occurring fracture in the sheet metal and the resulting expansion of the oil. Based on internal calculations this results in a cost-intensive test that is about five times more expensive compared to a standard Nakajima test. Furthermore, the used hydraulic oil is harmful and additional precautions must be taken.

In this paper an innovative strategy is proposed that holds the benefits of the hydraulic bulge test, while at the same time minimizing its disadvantages. To achieve this, a standard Nakajima test was modified by placing a measuring pin beneath the dome of the Nakajima punch (Fig. 1). Therewith it is possible to distinguish contact pressures between the testing material and the Nakajima punch of different materials by analyzing the resulting measuring signal of the measuring pin. This signal is based on the vertical micro-strains of the pin and depends therewith on normal and lateral forces acting on the punch. Therefore, it is not possible to use a uniform calibration of the measuring pin. To overcome this problem we propose to use an equibiaxial stress–strain curve derived by the hydraulic bulge test of a known material as a reference which can be used for calibration of unknown materials in a large range.

An additional challenge for this strategy is the occurring friction in Nakajima tests. Even we can reduce the friction coefficient by suitable measures as discussed in Section 2.4, the friction cannot be neglected when using the membrane theory for determination of the resulting stress state in the dome.

A first approach was published by Tamer et al. [8]. Therein the authors predicate virtually friction and equibiaxial flow stress by

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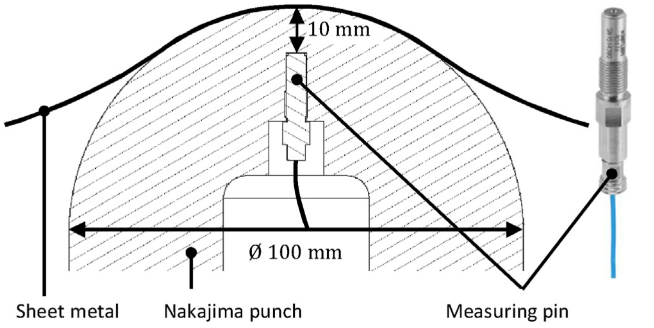

Fig. 1. Nakajima punch equipped with a measuring pin [11].

simulating a stretching of sheet metals over a modified Nakajima punch with an intermediate polyurethane disc. The Nakajima punch was equipped by a load cell which is loaded by a separate cylindrical insert of the punch, replacing the hemispherical dome region. Measuring the forces that occur on the load cell, the authors predicate equibiaxial flow curves. The results are obtained by an inverse parameter identification using a basic material description with simulation. Thus, some open questions are left: how does the polyurethane disc affect the measurement of forces? How accurate must the first material parameter assumptions be? How do the shape and the size of the insert affect the test? Is the test setup feasible for real tests? Even this approach is interesting, a direct evaluation method without inverse parameter identification is desirable.

Thus, in this paper a fundamentally different approach is proposed to determine equibiaxial flow curves with the Nakajima test. The calibration of the measuring pin signal is done directly by using only known information of a reference material. We demonstrate that this calibration function is suitable to analyze an unknown material even with significant different material properties. Following this, the resulting stress–strain curve up to equivalent strains of 50% ... 60% is practically for free, because the standard tensile test and the Nakajima test for the FLC determination of a new material are typically available anywhere. You only need a modified Nakajima punch with a measuring pin, which leads to a one-off expenditure solely. This highlights the industrial relevance of the new evaluation methodology.

2. Materials and methods

2.1. Notation of stress and strain

Suitable definitions for equivalent strains and stresses are necessary for an extrapolation of the uniaxial flow curve based on an equibiaxial flow curve. All of the following stresses are Cauchy-stresses σ, also known as true stress. For the extrapolation the longitudinal stress of the uniaxial tension test σ_{uni} are compared to the mean of the nearly equal in-plane stresses σ_x, σ_y in the equibiaxial experiments σ_{bi}:

$$\sigma_{bi} = \frac{\sigma_x + \sigma_y}{2} \tag{1}$$

According to Ref. [9], the negative of the plastic logarithmic thickness-strain for the equibiaxial experiments as well as the longitudinal plastic logarithmic strain for the uniaxial tests are the values of the equivalent logarithmic plastic strain ε.

2.2. Innovative measurement method: modified Nakajima punch

The standard Nakajima test, which was standardized in Ref. [10], is currently used for the determination of forming limit strains under different strain states between the uniaxial and the equibiaxial tension. So far no direct evaluation of stresses is possible. To enable an evaluation of stresses, the standard Nakajima punch was equipped with a miniature longitudinal measuring pin (Kistler Instrumente AG, Type 9247A) that is shown in Fig. 1 [11].

The elastic deformation of the pin can be determined with aid of this measuring pin that is based on the piezoelectric effect. The measuring pin was screwed in the Nakajima punch with a certain preload. For that reason the deformation of the pin is directly correlated to the resulting vertical elastic deformation of the punch, which depends on vertical and lateral forces due to the 3D elastic behavior of the punch.

With this setup, standard Nakajima samples of different materials were tested. Due to the different strengths of varying materials, punch stroke dependent, distinguishable deformations of the measuring pin result. Using the DIC system, material strains over punch stroke can be evaluated simultaneously. Based on that, the measuring pin signal over strain can be measured for different materials and for different Nakajima specimen representing different strain states.

2.3. New idea to determine equibiaxial stress–strain behavior

The basis for the proposed approach is a reference material with uniaxial and equibiaxial stress–strain behavior determined by uniaxial tensile test and hydraulic bulge test, respectively. In this paper the reference material is the dual phase, high-ductility steel CR330Y590T-DH with sheet thickness of 1.0 mm; in the following the reference material is abbreviated to “DH”.

The objective of the approach is to predict the equibiaxial stress-strain behavior of another, unknown material – here the micro-alloyed steel CR300LA with a sheet thickness of 1.0 mm, abbreviated to “LA” – without the necessity of processing the hydraulic bulge test. The prediction is based on the equibiaxial stress–strain behavior of the reference material $\sigma_{\mathrm{bi,DH}}(\varepsilon)$ as well as the measuring pin signals of Nakajima specimen under equibiaxial strain of both materials $S_{\mathrm{bi,LA}}(\varepsilon)$ and $S_{\mathrm{bi,DH}}(\varepsilon)$

Since friction influences the Nakajima test more than the hydraulic bulge test, a calibration function C is necessary. Therewith, the following key equation for the determination of the unknown equibiaxial stress–strain curve follows:

$$\sigma_{\mathrm{bi,LA}}(\varepsilon) = \sigma_{\mathrm{bi,DH}}(\varepsilon) \cdot \frac{S_{\mathrm{bi,LA}}(\varepsilon)}{S_{\mathrm{bi,DH}}(\varepsilon)} \cdot C(\varepsilon) \tag{2}$$

In this approach we utilize the different behavior of the two materials in the conventional tensile test and the Nakajima setup under uniaxial load to determine the calibration function. The prerequisite of this method is a comparable lubrication system for the equibiaxial and uniaxial Nakajima test specimens. Following this, for both materials the known stress–strain behavior $\sigma_{\mathrm{uni,DH}}(\varepsilon)$ and $\sigma_{\mathrm{uni,LA}}(\varepsilon)$ as well as the measuring pin signals of Nakajima specimen under uniaxial tension $S_{\mathrm{uni,DH}}(\varepsilon)$ and $S_{\mathrm{uni,LA}}(\varepsilon)$ are compared. Consequently, the calibration function can be derived as follows:

$$C(\varepsilon) = \frac{\sigma_{\mathrm{uni,LA}}(\varepsilon)}{\sigma_{\mathrm{uni,DH}}(\varepsilon)} \cdot \frac{S_{\mathrm{uni,DH}}(\varepsilon)}{S_{\mathrm{uni,LA}}(\varepsilon)} \tag{3}$$

Fig. 2 schematically summarizes the innovative approach to determine equibiaxial flow curves of sheets with a modified Nakajima test.

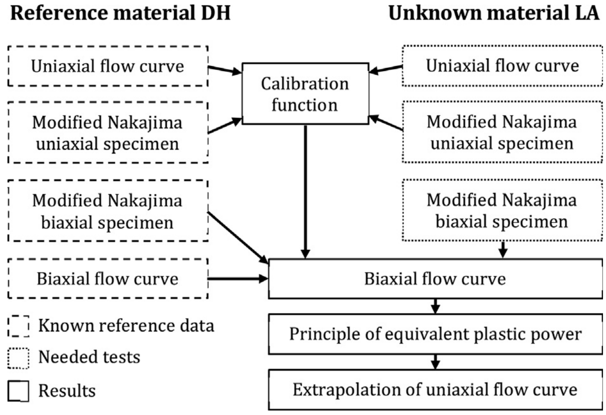

Fig. 2. Scheme of the innovative approach.