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Development of autonomous experimental setup to investigate directional distortional hardening under biaxial loading

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This paper describes the experimental determination of yield surfaces (YS) in a cold drawn steel. YS bounds the elastic domain in the stress space. By reaching the surface, plastic strains occur and the YS changes in the position, size and/or shape. This phenomenon is referred as strain hardening. In the field of phenomenological plasticity theory, the elementary mechanisms of strain hardening are kinematic hardening *(translation of YS)* and isotropic hardening *(uniform expansion of YS)*. However, it has been experimentally proven that other processes such as distortion, rotation, and/or affine deformation are usually present and affect the shape of the YS [1, 3, 5].

Directional distortional hardening (DDH) is a well known mechanism of strain hardening. It is characterized by the YS developing a region of a high curvature in the direction of loading and a flattening at the rear part of the YS, Fig. 1. The yield function of the DDH model proposed by Feigenbaum and Dafalias in 2008 [2] is as follows

$$f = (\boldsymbol{s} - \boldsymbol{\alpha}) : \boldsymbol{\mathcal{H}} : (\boldsymbol{s} - \boldsymbol{\alpha}) - k^2 = 0, \tag{1}$$

where $\boldsymbol{s}$ is the deviatoric stress tensor, $\boldsymbol{\alpha}$ is the back-stress tensor, and k is the size of YS. $\boldsymbol{\mathcal{H}}$ is a fourth order tensor-valued internal variable used to model distortion. The tensor $\boldsymbol{\mathcal{H}}$ distinguishes this model from classical concept of isotropic and kinematic hardening. This model is thermodynamically consistent and was employed to model and predict multiaxial ratcheting, as reported by Welling et al. [4].

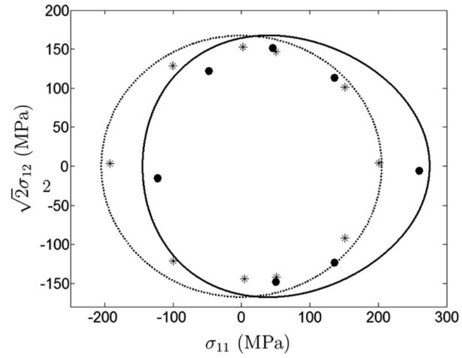

Fig. 1. DDH model for initial and subsequent YS; figure adopted from reference [2]

The aim of the experimental work is to develop a fully automated method for tracing YS with the ability to flexibly vary keys parameters such as specimen dimensions, stress rates, system of probing paths, etc. The experimental setup to capture the YS consists of an axial-torsional universal hydraulic testing machine by Instron company, a biaxial extensometer, and a desktop computer with software for data evaluation and machine control. Methods for tracing initial YS were developed in two separate softwares – Wavematrix2 (WM) and Labview 2017 (LV). Although the proprietary Instron WM software proved it's suitability for automated procedure for capturing yield surfaces [3], LV shows much more promise in terms of advanced parametrization. The results obtained from both software proved to be consistent and therefore only results acquired by LV are presented. The measurements were carried out on the thin-walled tubular specimens.

The YS tracing method consists in capturing a series of yield points according to a yield condition in the form of effective plastic strain

$$\varepsilon_{\text{eff}} = \sqrt{\left(\varepsilon^{\text{tot}} - \frac{4F}{\pi\left(D^2 - d^2\right)E} - \varepsilon^{(0)}\right)^2 + \frac{1}{3}\left(\gamma^{\text{tot}} - \frac{16DT}{\pi\left(D^4 - d^4\right)G} - \gamma^{(0)}\right)^2}, \qquad (2)$$

where ε^{tot} and γ^{tot} are total axial and shear strain respectively. The fractions in this equation are the elastic axial and shear strains, writen in terms of force, F, torque, T, outer diameter, D, inner diameter, d, and elastic moduli, E and G; $\varepsilon^{(0)}$ and $\gamma^{(0)}$ are the offsets. The specimen is subjected to a stress-controlled loading from the centrepoint at zero stress until the yield condition is reached and, consequently, unloaded back to the origin. This process is called probing. In the current measurement, the order and number of probes were chosen in accordance with Dietrich and Kowalewski [1]. More detailed information about the methodology can be found in [3, 5]. The results evaluated by the application developed in graphical programming software Labview are shown in Fig. 2. The stress space with the factor of $\sqrt{3}$ multiplying the shear was chosen so that the von Mises model would lead to a circular shaped YS.

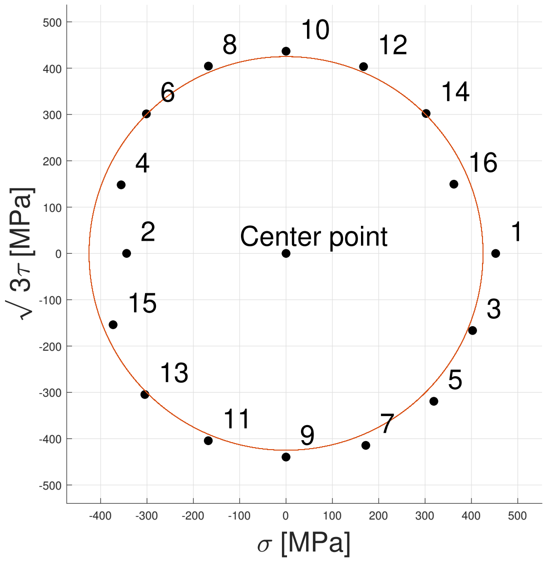

Fig. 2. Yield points measured with the experimental setup with comparison of von Mises yield surface in Axial stress – Shear stress space

The experimental results (in Fig. 2) show promising agreement with the von Mises yield surface model. A possible reason for the lower yield point (2) in the compressive loading direction is the manufacturing history, due to the fact, that the specimen used is made of cold drawn steel. Outlying points (4, 15, 16) violate the assumption of convexity of the YS. Therefore, the effect of cyclic strain hardening *(probing effect)* and the effect of automatic continuous least square regression for determination of the elastic moduli are being examined. The method is under further development.

Acknowledgements

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