27/28th International Conference
ENGINEERING MECHANICS 2022
Milovy, Czech Republic, May 9 –12, 2022
Paper **#64**, pp. 393–396, doi: 10.21495/51-2-393

DEVELOPMENT OF AUTONOMOUS EXPERIMENTAL SETUP TO INVESTIGATE DIRECTIONAL DISTORTIONAL HARDENING UNDER BIAXIAL LOADING

Svárovský J.[*], Parma S.[*], Štefan J.[*], Ciocanel C.[**], Feigenbaum H. P.[**], Marek R.[*], Klepač V.[*], Plešek J.[*]

Abstract: *Experimental measurements focused on the evolution of yield surfaces during strain hardening are crucial for the development and validation of phenomenological models of directional distortional hardening. This paper presents a method for yield surface tracing using axial-torsional universal testing machine Instron 8852 controlled by in-house software developed in visual graphical environment Labview 2019. Four yield surfaces were traced on a single specimen to which different level of prestrain were applied. Each yield surface was traced with four repetitions. Obtained data shows high level consistency across repetitions a exhibits characteristic features of directional distortional hardening. Small deviation of initial yield surface from the von Mises model was observed.*

Keywords: Yield surface, Strain hardening, Directional Distortional Hardening, Metal, Plasticity.

1. Introduction

The subject of this paper is the development of an advanced experimental method for measuring the evolution of yield surface (YS) under complex loading modes in metallic materials. The YS is defined as a surface which bounds the elastic domain in the stress space. The shape and position of the YS are altered by induced plastic strains, referred to as strain hardening, *cf.* (Wu and Yeh, 1991). The elementary mechanisms of strain hardening are kinematic hardening (translation of YS) and isotropic hardening (uniform expansion of YS), however, more complex shape and size changes have been found during experimental investigations. The development of a region with a high curvature in the loading direction and flattening at the posterior part of the YS is referred to as directional distortional hardening (DDH). Thermodynamically consistent phenomenological model of the DDH was proposed by Feigenbaum and Dafalias (2007) and was employed to model and predict multiaxial ratcheting, as reported by Welling et al. (2017). The convexity of model's yield surface was proved by Plesek et al. (2010), and, subsequently, the model was implemented by Marek et al. (2015) in a finite element code.

2. Testing Setup

The experiment was conducted using an axial-torsional testing system Instron 8852. The testing system consists of universal hydraulic testing machine (UTM), control unit and computer. The UTM has an axial load capacity of ± 100 kN and a torque capacity of ± 1000 Nm. Communication between the UTM and the PC is provided by a two-axis 8800MT digital controller via the Console software for full system control from the computer. The Console software is also controllable through APIs using other programs, either proprietary software by Instron (WaveMatrix2, Bluehill Universal) or in-house software. For this experiment, software was developed in the labview programming environment to control the UTM during YS

[*] Department D4 - Impact and Waves in Solids, Institute of Thermomechanics of the CAS, v. v. i.,Dolejškova 1402/5; 182 00, Praha 8; CZ svarojir@it.cas.cz
[**] Mechanical Engineering Department, Northern Arizona University, 15600 S. McConnell Dr. NAU, Flagstaff, AZ 86001-5600, US

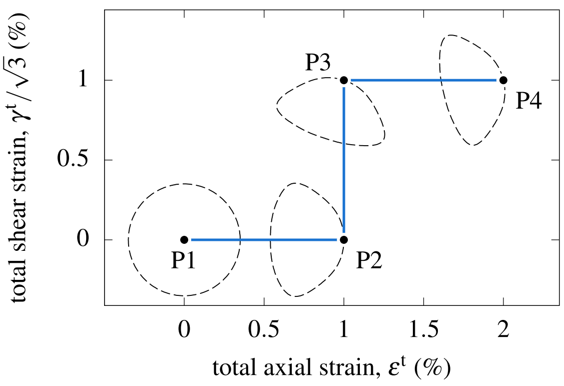

Fig. 1: A series of straining steps to induce strain hardening and distort yield surfaces.

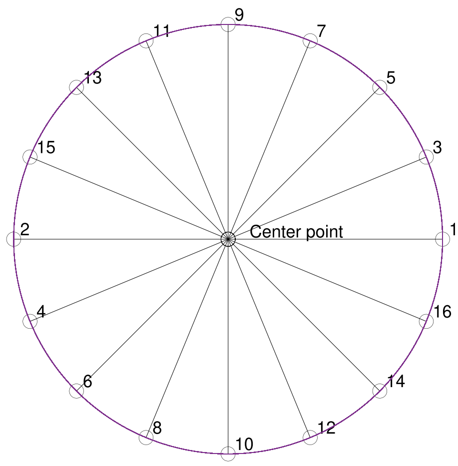

Fig. 2: A system of probing paths after Dietrich and Kowalewski (1997) to detect YS shape.

tracing. An integral part of the testing equipment is a biaxial contact extonsometer Epsilon Tech 3550 for measuring axial a shear strain on the test specimen. More details on experimental setup might be found in (Štefan et al., 2021).

3. Test Specimens and Materials

Experimental measurements were carried out on thin-walled tubular test specimens (TS) that have been manufactured from a round bar of 304L steel with diameter of 40 mm. The outer surface of the TS was CNC machined and finished by lapping. The inner hole was made by electrical discharge machining. The end sections of the TS were filled with steel pin insert during the experiment to prevent failure due to the acting force of the hydraulic grips.

4. Methodology

In this work, yield surfaces were distorted by a series of plastic straining steps shown in Figure 1. After each straining step, a shape of distorted yield surface was traced. The method for Yield Surface tracing consists of measuring a series of yield points under prescribed combinations of axial load and torque. Process of capturing of a single yield point is referred to as probe and the chosen probing system is shown in Figure 2.

The specimen is submitted to slow stress-controlled loading from the center point (CP) with a given proportional combination of normal and shear stress according to the probing system until the yield conditions is reached, then unloaded to the initial state. Stress state in thin-walled tubular TS is as follows:

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} = \begin{bmatrix} \sigma & \tau & 0 \\ \tau & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{1}$$

From that the von Mises yield criterion for a thin-walled tubular TS can be simplified to:

$$\sigma_{\mathrm{y}} = \sqrt{\sigma^2 + 3\tau^2} \tag{2}$$

where true axial a shear stresses are replaced by engineering quantities:

$$\sigma = \frac{4F}{\pi(d_{\mathrm{o}}^2 - d_{\mathrm{i}}^2)} \tag{3}$$

$$\tau = \frac{16 T d_{\mathrm{o}}}{\pi(d_{\mathrm{o}}^4 - d_{\mathrm{i}}^4)} \tag{4}$$

F and T represent axial force and torque, respectively, d_o and d_o represent the outer and inner diameter of the specimen. The fundamental stress rate remains constant for each probe:

$$\dot{\sigma}_{\text{fund}} = \sqrt{\dot{\sigma}^2 + 3\dot{\tau}^2} = 1.5\,\text{MPa s}^{-1} \tag{5}$$

Yield points are defined by small proof strain condition:

$$\varepsilon_{\text{eff}} = \sqrt{\left(\varepsilon^{\text{tot}} - \frac{4F}{\pi\,(D^2 - d^2)\,E} - \varepsilon^{(0)}\right)^2 + \frac{1}{3}\left(\gamma^{\text{tot}} - \frac{16DT}{\pi\,(D^4 - d^4)\,G} - \gamma^{(0)}\right)^2} \geq 50\mu\varepsilon, \tag{6}$$

here 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.

In the case of the initial yield surface (IYS), the specimen is loaded from the zero stress state. Subsequent yield surfaces (SYS) tracing is preceded by prestraining the TS to the desired state and the new CP must be found due to the translation of the YS. Prestraining consists of slow strain-controlled loading at a rate of 0.1 % per second until required level of axial and shear plastic strain is reached and then the specimen is held at that level for ten minutes. During this period, stress is relaxed and the final stress state defines approximate forward yield point (FYP). Subsequently, the specimen is unloaded from the FYP in the direction of the relaxation until the small proof strain condition is achieved, thereby finding the approximate reversed yield point (RYP). The new CP is located midway between the FYP and the RYP. Each YS is traced with four iterations, with the first tracing used to determine its precise ceter point (centroid) in postprocessing and subsequent iterations performed with this CP. For details on testing methodology, the reader is referred to an overview by Marek et al. (2022).

5. Results

During this experiment, the initial yield surface and three subsequent yield surfaces were measured successively on one specimen, with four repetition for each YS. The three levels of prestrain (Figure 1) applied for each SYS were as follows: 1 % axial prestrain; 1 % axial prestrain and 1 % shear prestrain; 2 % axial prestrain and 1 % shear prestrain respectively. The magnitude of the small proof strain condition was chosen to be $\varepsilon_{\text{eff}} \geq 50\,\mu\varepsilon$, as a compromise between the stability of the calculation and the minimum effect on the plasticity surface. The determination of the exact geometric center (centroid) of each surface is shown in the Figure 3, and following repetitions of the measurements were performed with the found center point. Figure 4 shows the initial and subsequent yield surfaces measured using the above methodology.

6. Discussion

As the results in Figure 4 exhibit, a functional methodology has been developed to trace the yield surfaces and their evolution due to the effect of strain hardening. The measured IYS deviates from von Mises model by small elongation in the shear load direction, but overall achieves high level agreement. The elongation can either be caused by residual stress in the specimen that was already present in the semiproduct or introduced during machinig of the TS. Another possible reason for deviation from the model may be due to

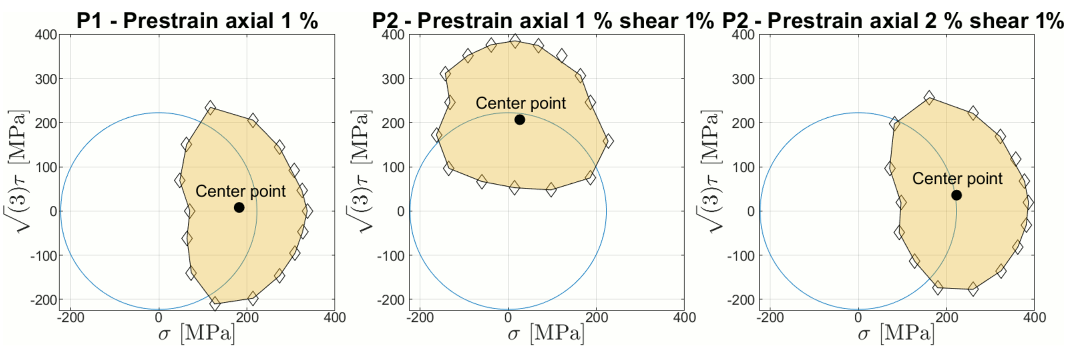

Fig. 3: Determination of the geometric centre - center point

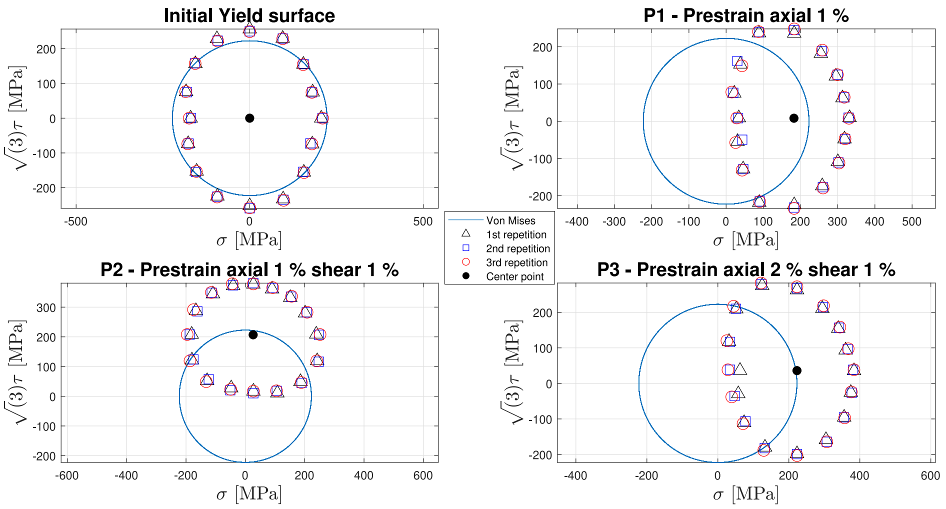

Fig. 4: Yield surface evolution—initial YS and subsequent yield, three repetitions per surface surfaces

imprecise strain measurements or inaccurate automatic evaluation of elastic moduli. This is subject to further investigation. All measured SYS have evidence of DDH in the form of elongation of the yield surface in the prestrain direction, and flattening in the opposite direction. The obtained data shows strong consistency across repetitions. Experimental data gained within this work might be used to calibrate plasticity models using algorithms developed by Parma et al. (2018). Also, the effect of directional distortional hardening is considered to be significant in multiaxial ratcheting, as reported by Dafalias and Feigenbaum (2011).

Acknowledgments

Jiří Svárovský and Slavomír Parma acknowledge support by MEYS CR under grant project Centre of Excellence for Nonlinear Dynamic Behaviour of Advanced Materials in Engineering—CeNDYNMAT, grant No. CZ.02.1.01/0.0/0.0/15_003/0000493. René Marek acknowledges support by MEYS CR under grant No. LTA USA 18199. Heidi P. Feigenbaum and Constantin Ciocanel acknowledge support by the US Army Research Laboratory and the US Army Research Office under Grant No. W911NF-19-1-0040. Vilém Klepač and Jiří Plešek acknowledge support by the Institute of Thermomechanics of the Czech Academy of Sciences, grant No. RVO:61388998.

References

Dafalias, Y. F. and Feigenbaum, H. P. (2011) Biaxial ratchetting with novel variations of kinematic hardening. *International Journal of Plasticity*, **27**, 4, pp. 479–491.

Dietrich, L. and Kowalewski, Z. (1997) Experimental investigation of an anisotropy in copper subjected to predeformation due to constant and monotonic loadings. *International Journal of Plasticity*, **13**, 1–2, pp. 87–109.

Feigenbaum, H. P. and Dafalias, Y. F. (2007) Directional distortional hardening in metal plasticity within thermodynamics. *International Journal of Solids and Structures*, **44**, 22, pp. 7526–7542.

Marek, R., Parma, S., and Feigenbaum, H. P. (2022) Distortional hardening cyclic plasticity—Experiments and modeling. In: Jahed, H. and Roostaei, A. A., eds, *Cyclic Plasticity of Metals: Modeling Fundamentals and Applications*, Elsevier.

Marek, R., Plešek, J., Hrubý, Z., Parma, S., Feigenbaum, H. P., and Dafalias, Y. F. (2015) Numerical implementation of a model with directional distortional hardening. *Journal of Engineering Mechanics (ASCE)*, **141**, 12, pp. 04015048-1–04015048-10.

Parma, S., Plešek, J., Marek, R., Hrubý, Z., Feigenbaum, H. P., and Dafalias, Y. F. (2018) Calibration of a simple directional distortional hardening model for metal plasticity. *Int. J. of Solids and Structures*, **143**, pp. 113–124.

Plesek, J., Feigenbaum, H. P., and Dafalias, Y. F. (2010) Convexity of yield surface with directional distortional hardening rules. *Journal of Engineering Mechanics*, **136**, 4, pp. 477–484.

Štefan, J., Parma, S., Marek, R., Plešek, J., Ciocanel, C., and Feigenbaum, H. P. (2021) Overview of an experimental program for development of yield surfaces tracing method. *Applied Sciences*, **11**, 16, pp. 7606.

Welling, C. A., Marek, R., Feigenbaum, H. P., Dafalias, Y. F., Plešek, J., Hrubý, Z., and Parma, S. (2017) Numerical convergence in simulations of multiaxial ratcheting with directional distortional hardening. *International Journal of Solids and Structures*, pp. 105–121.

Wu, H. C. and Yeh, W. C. (1991) On the experimental determination of yield surfaces and some results on annealed 304 stainless steel. *International Journal of Plasticity*, **7**, 8, pp. 803–826.