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An Experimental Investigation of Yield Surfaces Anisotropies

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Abstract. This contribution is dedicated to a rigorous experimental procedure for evaluation of yield surfaces of common metallic materials. This yield surface tracing procedure employs thin-walled tubular specimens to identify individual yield points of the material under arbitrary combinations of axial load and torque. A yield point is identified on the basis of a prescribed threshold for the effective plastic strain that is being continuously and fully automatically evaluated throughout the test. The experimental results generated with this tracing method are promising, leading to shapes of the yield surfaces conform with the von Mises criterion. The proposed methodology can effectively capture the YS shape.

Introduction

This work aims to establish a rigorous experimental procedure for evaluation of yield surfaces of common metallic materials. The concept of a yield surface is embedded in the phenomenological plasticity theory, and careful identification of yield surface shape is critical to the development and calibration of phenomenological models of plasticity [1–3]. In accordance with the theory, the yield surface (YS) can be defined as a region within a particular stress space bounding the elastic domain. When the stress state is elevated to a state on the YS, plastic flow occurs and the yield surface evolves. This is referred to as strain hardening. While evolving, the yield surface undergoes changes of size, position, and shape in a stress space that correspond to isotropic hardening, kinematic hardening, and distortional hardening, respectively.

Knowledge of YS shapes and their evolution under complicated modes of loading is useful for a number of applications including, but not limited to, the processes of forming of material products, and predicting the behaviour under cyclic loading (e.g., during earthquakes, in service conditions, repetitive wind or wave loading) leading to the accumulation of plastic strain. This is known as ratcheting. In particular, recent work [4] uses YS shape change to help develop models aimed at improving predictions of multiaxial ratcheting behaviour, since conventional models that neglect the YS distortion do not generally provide satisfactory predictions in this complex loading case. Experimental evaluation of strength anisotropy is also very important for additively manufactured materials [5].

Experiments

The experimental method in this work is based on mechanical testing of thin-walled tubular specimens under combined axial and torsional loading. Individual yield points constituting a yield surface within the axial stress – shear stress space ($\sigma - \sqrt{3}\tau$) are detected by performing a sequence of loads ("probes") characterized by particular levels of intensities of both loading components (i.e., the axial force, and the torque). Each probe indicates a yield point on the yield surface of the material under investigation. The experiments are conducted with an Instron-type biaxial testing machine and with an Epsilon-Tech biaxial contact extensometer enabling simultaneous measurement of axial and shear strains.

For the detection of a yield point, the approach presented in reference [6] was adopted. It is a type of proof strain method defining a yield point as a point for which a predetermined amount of von Mises effective plastic strain is developed. Under the combination of axial load and torque, the von Mises effective plastic strain reads

$$\Delta\varepsilon_{eff} = \sqrt{\varepsilon_{pl.}{}^2 + \frac{1}{3}\gamma_{pl.}{}^2}, \tag{1}$$

where the axial plastic strain $\varepsilon_{pl.}$and the shear plastic strain $\gamma_{pl.}$ are given, respectively, by

$$\varepsilon_{pl.} = \varepsilon - \varepsilon_{el.} - \varepsilon_R, \quad \gamma_{pl.} = \gamma - \gamma_{el.} - \gamma_R. \tag{2}$$

Here, the total strain components ε and γ are directly measured by the extensometer, the elastic strain components $\varepsilon_{el.}$ and $\gamma_{el.}$ are determined from load by making use of the Hooke's law, and ε_R and γ_R are residual strains as illustrated in Fig. 1.

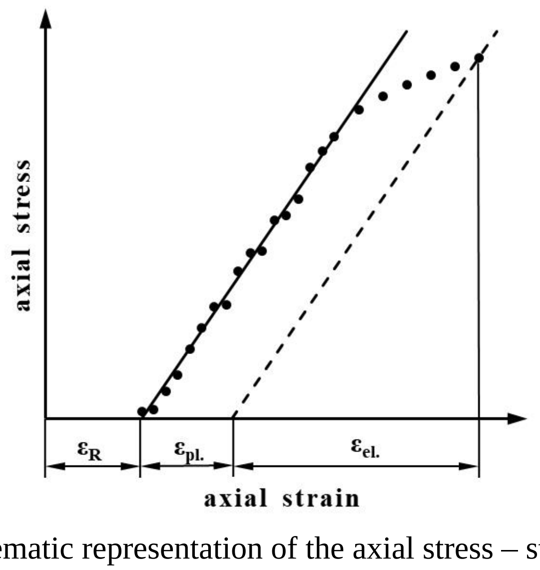

Fig. 1: Schematic representation of the axial stress – strain curve

In this work, the effective plastic strain threshold $\Delta\varepsilon_{eff} = 200\ \mu\varepsilon$ was used to define yielding. A vital part of the procedure is an algorithm that continuously and automatically performs a least squares linear regression analysis to fit the elastic part of the stress – strain curve during loading of the specimen. This algorithm has two primary outputs: the elastic moduli (E, G) as slopes, and the residual strains (ε_R, γ_R) as offsets. Actual values of elastic parts of strain ($\varepsilon_{el.}$, $\gamma_{el.}$) are calculated from the elastic moduli and subsequently used to evaluate the total effective plastic strain accumulated up to the current strain state of the specimen, via Eq. (2). Hence, the procedure is fully automatized for evaluating unique yield points. Once a yield point is detected, the loading ceases, the specimen is unloaded to a state inside the YS (generally a zero stress), and a new probing path is started; thus a single specimen is used to fully characterize a yield surface.

The experimental procedures presented herein were validated by performing evaluation of the initial yield surfaces of common metallic materials, i.e., evaluation of yield surfaces of materials in the as-manufacture state with no additional plastic pre-load. At first, a non-alloyed cold-drawn ferritic steel was used. In the second experiment, a hot rolled carbon steel of C60R grade (W. Nr. 1.1223) was investigated. The geometry of the test specimen used in these experiments is depicted in Fig. 2.

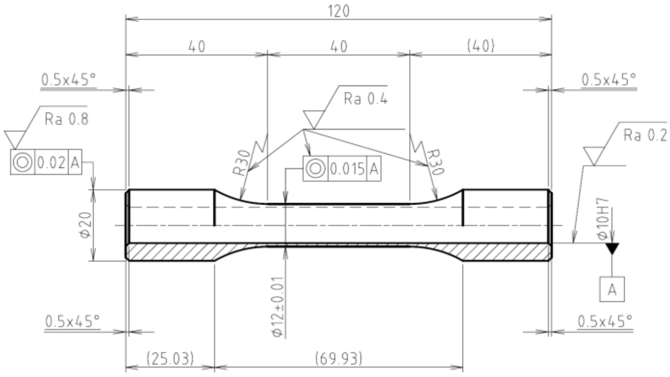

Fig. 2: Design and dimensions of the test specimen manufactured from C60R steel (the dimensions are stated in millimeters)

Results and discussion

Fig. 3 shows the yield surfaces evaluated on thin-walled tubular specimens manufactured from a non-alloyed ferritic steel (A), and on a carbon steel of C60R grade (B). The YS shapes reported in Fig. 3 are relatively well predicted by the von Mises yield criterion, as expected, because the material/specimen has not been pre-loaded. These preliminary results suggest that the proposed methodology proposed can effectively capture the YS shape.

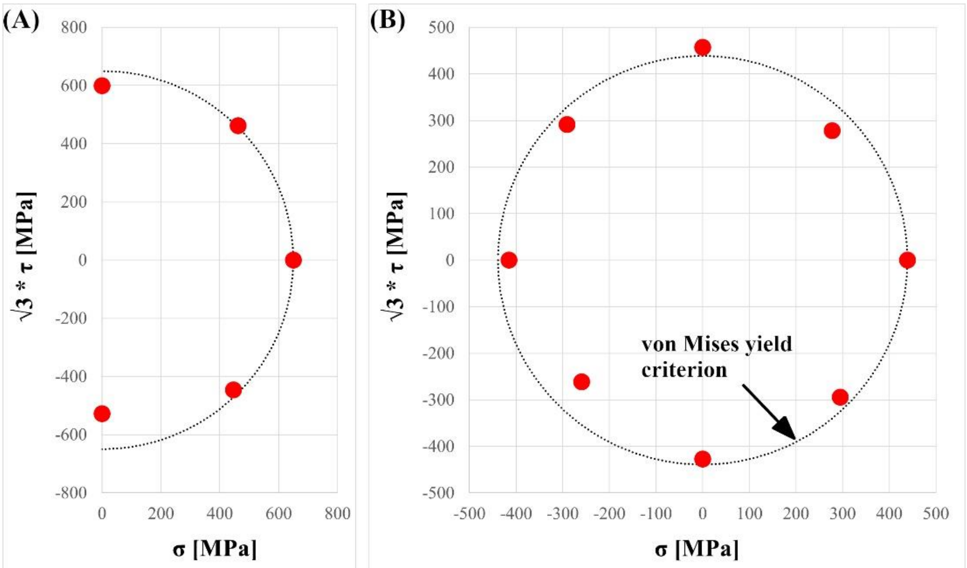

Fig. 3: A tensile part of the initial yield surface of a non-alloyed cold-drawn ferritic steel (A), and a full initial yield surface of a C60R steel (B)

Tab. 1: Results of yield surfaces tracing experiments.

Probe	Non-alloyed steel		C60R steel	
No.	σ_{YP} [MPa]	τ_{YP} [MPa]	σ_{YP} [MPa]	τ_{YP} [MPa]
1	649.5	0.0	438.8	0.0
2	0.0	346.1	–415.4	0.0
3	0.0	–304.9	0.0	264.0
4	462.2	266.8	0.0	–246.7
5	446.5	–257.7	277.8	160.6
6	—	—	295.3	–169.7
7	—	—	–291.0	168.3
8	—	—	–259.3	–150.7

Conclusions

In this paper, a rigorous experimental method for the evaluation of yield surfaces is presented. The method uses algorithms enabling continuous and fully automatized evaluation of elastic moduli and the actual amount of effective plastic strain, which are being used to calculate a threshold plastic strain which defines the trigger of a yield point. It was shown that the first couple of experiments performed on specimens of conventional metallic materials provided promising results as the yield surfaces shapes conformed with the von Mises yield criterion. Future work will focus on improving the method, characterizing other steels and capturing the YS distortion due to strain hardening under various pre-loads.

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