Strain hardening and microstrains during cyclic incremental forming of carbon steel and pure iron

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Abstract. The evolution of subsequent yield loci after large plastic strains has been studied for pure iron and steel with ferrite-pearlite structure. Large strains have been applied by torsion of thin walled tubes with different strain paths: monotonic and cyclic incremental torsion. Points on the yield loci have been probed by biaxial torsion-tension or torsion-compression load using a single-probe method. The results show strong influence of the microstructure towards anisotropic hardening. Microstrain values from XRD profile analysis are added and confirm the findings for hardening behaviour.

1. Introduction
In continuum mechanics, strain hardening is described by the model of the yield surface and its strain-dependent evolution. Translation, expansion and rotation or shape changes are denoted as kinematic, isotropic and distortive hardening, respectively. In complex strain paths with reversed strain, plastic yield can be strongly anisotropic, dependent on material and its microstructure [1]. A strong Bauschinger effect was reported for multiphased materials, and attributed to back stresses caused by microstrains. These microstrains can exist between grains and different phases (2nd order) and inside grains and phases due to dislocation arrangement (3rd order).

This study intends to compare strain hardening evolution of steel with a ferrite-pearlite structure and pure iron during different strain paths under large plastic shear strain. The influence of a second hard phase – the Fe₃C-lamellae in pearlite grains – towards path-dependent anisotropic hardening is to be demonstrated.

2. Experimental work

2.1. Material and sample shape
For the investigation of subsequent yield loci two materials have been choosen: steel 42CrMo4 with normalised ferrite-pearlite structure and commercial pure iron (0.009%C; 0.090%Mn; 0.005%P; 0.001%S) with grain sizes of 15µm and 30µm, respectively. The samples were thin walled tubes with inner and outer diameter of 10 and 12.5 mm, respectively and a deforming length of 10 mm.

2.2. Plastic pre-strain in torsion
Large plastic strains have been applied by free end torsion test at room temperature. Two different strain paths have been applied: Monotonic torsion and a cyclic incremental path with forward strain
amplitude $\gamma_+ = 0.26$ and backward strain amplitude $\gamma_- = 0.15$ at a shear strain rate of $0.08\, \text{s}^{-1}$. The maximum shear strain $\gamma$ was calculated from the rotation angle $\phi$, the outer sample diameter $d_o$ and the length $l$ to $\gamma = \phi d_o/2l$. The maximum shear stress was calculated from the measured torque $M$, assuming linear stress distribution versus the radius: $\tau = M/(\pi (d_o^4-d_i^4)/16d_o)$. The torsional strain paths were conducted up to certain strain stages, as indicated by points in figure 1a for steel.

2.3. Biaxial testing

At certain strain stages, the samples were partially unloaded before biaxial testing. Only partial unloading was essential steel to prevent plastic flow during complete unloading, as shown in [2]. Biaxial testing was done by combined torsion-tension or torsion-compression test, with torsion in prestrain and in opposite direction. With this procedure, subsequent yield points in the axial stress-shear stress space could be detected. A single-probe method was applied to exclude influences of yield probing procedure, because pre-strained material is very sensitive towards any further deformation. The method for yield point determination has been described in detail elsewhere [2]. Here, for initial yield points the instability in shear stress – axial stress plot was used as yield criterion and for subsequent yield points a $0.0005$ ($0.05\%$) v. Mises offset strain. Therefore, the strains had to be determined by optical strain field analysis using an Aramis system (by GOM company). Strains and stresses have been calculated using the current sample geometry. The equivalent strain rate for biaxial testing was $0.01\, \text{s}^{-1}$.

For prestrain and biaxial testing a hydropuls tension-torsion testing machine SchenckPTT250 was used.

2.4. Microstrain determination

Microstrains have been calculated from XRD profile Rietveld-analysis using the Diffrac plus-TOPAS (4.2) software from Bruker axs. Diffraction profiles were measured on flat grinded and polished mantle surfaces of the thin walled tube samples using a Siemens D5000 diffractometer and CoK$\alpha$ radiation. Microstrains have been derived using only Gaussian contribution to the line profile adjustment.
3. Results

3.1. Strain hardening

Torsional flow curves show the dependency of flow stress on the strain path, figure 1a. The cyclic forming paths lead to reduced flow stresses compared to the monotonic deformation. For steel, strain reversal results in early re-yielding and considerable strain hardening (as slope of the flow curve, $\Delta \tau / \Delta \gamma$) during each deformation step. Pure iron, however, shows a much smaller slope $\Delta \tau / \Delta \gamma$ and yield stresses, which are almost not influenced by strain reversal. The shape of the hystereses can be compared more clearly in figure 1b, where the stresses are normalised with the first yield shear stress.

The yield loci of the two materials in shear stress-axial stress space are depicted in figures 2-5.

Figure 2 shows the initial yield loci. The experimental points allow the construction of ellipses with nearly ideal v. Mises axial ratio. When a torsional prestrain was applied, expansion, distortion and translation of the yield loci into last prestrain direction appear, the latter especially distinct for steel. The shapes of the yield loci have been constructed by means of the experimental points, using simple geometric forms. During the cyclic incremental strain path, the subsequent yield locus expands, translates according to the strain path, and generates a higher curvature towards the last prestrain.
direction, figures 2-5. All hardening components are visible in both materials, whereas isotropic hardening dominates in pure iron and anisotropic hardening in steel. The influence of strain path at a certain resulting deformation is shown in figure 5. The cyclic strain paths lead to a shrinking dimension of the yield loci regarding the pre-strain axis by early re-yielding, especially for steel.

3.2. Microstrains
Microstrains are increasing during deformation, whereas backward strain lowers them in the beginning of the cyclic incremental strain path, figure 6. For both materials, the strongest increase of microstrains occurs in the first strain step towards $M_1$, where the flow stress increases remarkably. Afterwards, alterations are smaller. For steel the dependency of microstrain value on the forming path is more pronounced than for iron, forward compared to backward strain stages as well as cyclic compared to monotonic deformation are clearly different. For iron, the strain states $B_6$, $F_6$ and $M_6$ lead to similar microstrains.

![Image of microstrains](image.png)

Figure 6. Microstrains of steel and pure iron at different strain stages (see figure 1a). Microstrains have been normalised to the value for the initial state (heat treated). The initial values are 0.024% and 0.030% for iron and steel, respectively.

4. Conclusions
During large plastic deformation of steel and pure iron with reversed strain all hardening components have been found: Isotropic and anisotropic hardening, which comprises translation and distortion of yield loci. Cyclic incremental deformation of steels leads to strong anisotropic hardening. This is due to the second hard phase in steel, which cause strong path-dependent microstrains. Subsequent yield loci of the single-phased iron show mainly isotropic hardening, anisotropic hardening portions are small, but visible. The less path-dependent microstrains, which are present in pure iron, therefore may arise from dislocation pattern or inter-grain strains. Transmission electron microscopy has to substantiate these findings.

Acknowledgement
The authors acknowledge the DFG for supporting this work carried out within the framework of project SPP 1146.

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