Ferrite slip system activation investigated by uniaxial micro- tensile tests

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Abstract

Well-defined uniaxial micro-tensile tests are performed on single-crystal ferrite specimens with three different orientations. All specimens reveal a highly reproducible plastic behavior. The {110}<111> and {112}<111> slip systems equally contribute to the deformation, while all other (complex) slip traces can be identified as cross-slip and 'pencil glide'. No {123}<111> slip system traces were observed. The critical resolved shear stresses of the two active slip systems are close to each other, i.e. CRSS {110} = (1.0±0.1)×CRSS {112} . In all the tested specimens, the activation of the primary slip systems (e.g. systems that activate first) follows the conventional Schmid's law. At first glance, the activation of secondary slip systems does not seem to comply with the highest Schmid factor. However, detailed investigation reveals that the boundary constraints acting on the primary slip system triggers an increase of the Schmid factors of the activated secondary slip systems, i.e. Schmid's law correctly justified all observed slip traces. Additionally, detailed crystal plasticity simulations have been added that confirm the finding from the experimental and give a wealth of new insight into ferrite crystal plasticity.

Introduction

The plasticity of ferrite, iron with Body-Centered-Cubic (BCC) structure, is considerably more complex than plasticity in its Face-Centered-Cubic (FCC) counterpart austenite. As in most BCC transition metals, ferrite plasticity is governed by glide of screw dislocations, which are not confined to a well-defined glide plane. Moreover, due the non-close packed nature of the BCC lattice, there is more than one candidate slip family. As a consequence, plastic deformation results in wavy and curved slip traces, which make the identification of the exact slip systems challenging.

In this study, we perform a series of uniaxial micro-scale tensile tests on single crystal ferrite micro-specimens by employing a highly accurate nano-force tensile tester to quantify the slip activity at the micro scale, while simultaneously acquiring the specimen's stress-strain response.[1,2,3,4] Crystal plasticity simulations of the tested micro-specimens are used to study influence of the experimental boundary conditions.[5] The focus will be on the identification of the active slip systems and the investigation of the order in which different slip systems are being activated and the role of boundary constraints therein. It will be shown that the activation of slip systems, either from the {110}<111> or {112}<111> family, is controlled by the interaction between slip system directions and active boundary constraints.

Results and conclusion

Single crystal ferrite micro-specimens of different orientations were tested with a nano-force tensile stage, see Fig. 1. Reproducible results within statistics were obtained in all the test orientations. Based on the slip trace and stress-strain analysis of the specimens, the following conclusions are drawn:

(1) Both the {110}<111> and {112}<111> slip systems contribute to the deformation, while {123}<111> family is not activated. For both the {110}<111> and {112}<111> family, the primary slip system or systems were consistently the ones with the highest Schmid factors.

(2) The CRSS of the {110}<111> and {112}<111> slip systems are close to each other and the following ratio has been identified: $CRSS_{\{110\}} = (1.0 \pm 0.1) \times CRSS_{\{112\}}$.

(3) Second slip systems, i.e. slip systems that activate at later stage during in the deformation are necessary to accommodate the applied boundary constraints. At first glance, these slip system appear to exhibit anomalous slip activity, as their initial Schmid factor is low. Careful analysis revealed that the actual Schmid factor must be (much) higher due to the increase in resolved shear stress due to the elastic strain caused by the combination of primary slip plasticity and boundary constraints, i.e. Schmid's law is still valid.

Crystal plasticity simulations of specimens having the same crystallographic orientations (G1 and G3) as in the experiments and reflecting the experimental boundary conditions (with different degrees of constraining) show that constraining effects (and thus the exact boundary conditions) play a key role in the determination of the slip activity within the specimen, and can affect the macroscopic stress-strain response, see Fig. 2. Therefore the crystal plasticity simulations confirm the experimental findings. Moreover, these detailed crystal plasticity simulations provide deep insights in ferrite crystal plasticity.

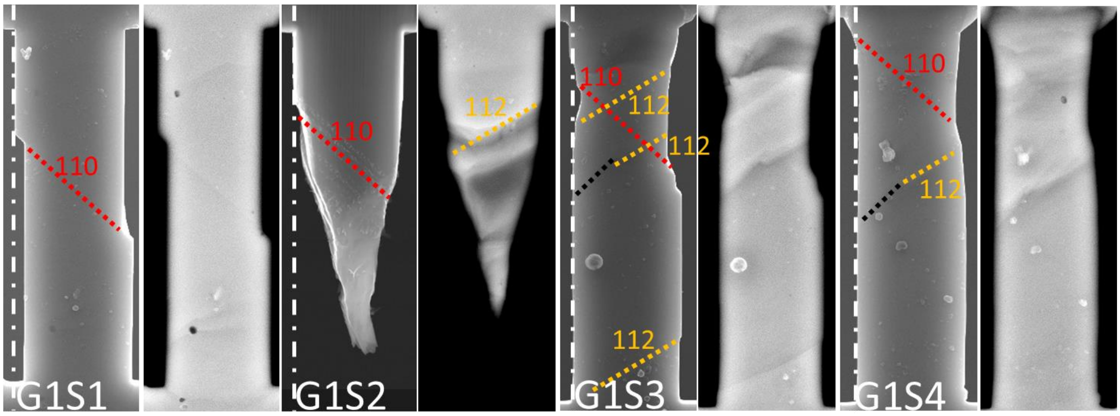

Figure 1: A typical example of a series of micro-tensile tests on ferrite specimens that came all from the same crystal, and therefore have exactly the same crystal orientation. Front side SE and BSE images of deformed specimen gauge section. G1S1 refers to Specimen 1 from Grain 1. The slip traces are marked with colors: red represents the primary slip system(s) which is/are activated first, orange the secondary slip system(s). Black lines represent the trace of a slip plane that does not belong to the {110}<111> or {112}<111> families. The vertical dash-dotted lines at either the left or right edge of each SE image help to visualize the shape of the deformed specimens: 'sheared' or 'straight', which corresponds to an unconstrained (UB) and constrained (CB) boundary condition. G1S2 is the only specimen loaded to fracture for which the left SE image shows the backside, for which the {110}<111> slip trace is more clearly visible.

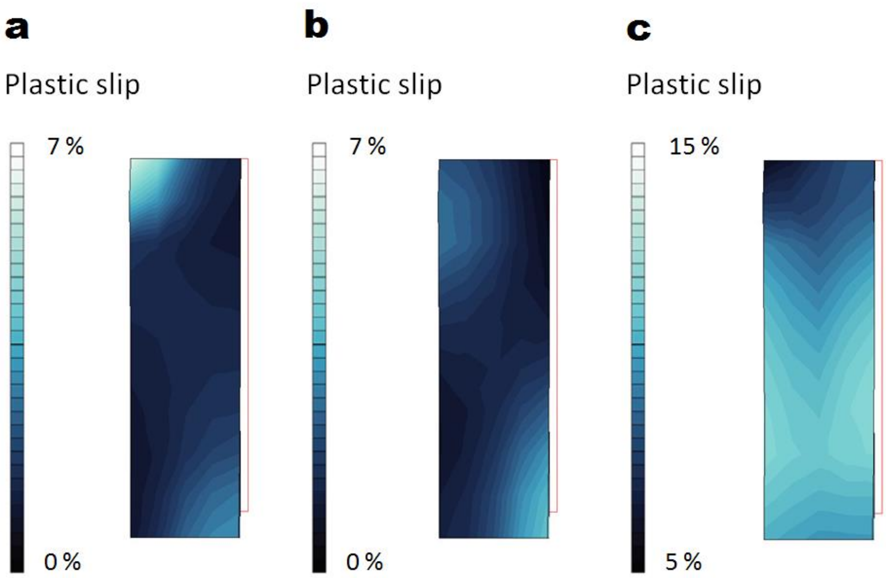

Figure 2: A typical example of the type of crystal plasticity results that have been obtained to enable a one-to-one comparison with the micro-tensile experiments: Plastic slip activity one of the constrained specimens, e.g. G1S3 or G1S4. (a) Activity of the $(1\bar{1}0)[11\bar{1}]$ slip system; b. Activity of the $(110)[\bar{1}11]$ slip system; and c. Activity of the $(\bar{1}20)[11\bar{1}]$ slip system.

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