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Regular Article

Suppressed martensitic transformation under biaxial loading in low stacking fault energy metastable austenitic steels

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ABSTRACT

The effect of uniaxial/biaxial loading on the martensitic transformation of a low stacking fault energy, metastable austenitic stainless steel was studied by in-situ neutron diffraction on cruciform-shaped/dogbone samples. Uniaxial loading favors the martensitic transformation following the sequence $\gamma \rightarrow \varepsilon \rightarrow \alpha'$, where at low strains ε-martensite is the precursor of α′. During equibiaxial-loading, the evolving texture suppresses the formation of ε-martensite and considerably less α′-martensite is observed at high strains. The results are discussed with respect to the deformation textures, the loading direction and the mechanism of the ε-martensite transformation.

In metastable austenitic stainless steels martensite forms upon deformation, the so-called transformation induced plasticity or TRIP effect, and this transformation is responsible for a good combination of strength and ductility that these materials exhibit. Two types of martensite can be formed during deformation: the hexagonal-closed-packed (hcp) ε-phase and the body-centered-cubic/tetragonal (bcc or bct) α′-phase. For some steels, it has been reported that ε-martensite is a precursor of α′-martensite as it forms at early stages of plastic deformation and that α′ forms at later stages of deformation in expense of ε-martensite [1–4]. For other steels the direct formation of $\gamma \rightarrow \alpha'$ has been reported [5]. Generally it is believed that the prevalence of $\gamma \rightarrow \varepsilon \rightarrow \alpha'$or $\gamma \rightarrow \alpha'$ depends on the stacking-fault-energy (SFE) of the austenitic phase: for low SFE steels (<20 mJm^{-2}) the sequence $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ is favorable whereas for high SFE steels (>20 mJm^{-2}) the direct $\gamma \rightarrow \alpha'$ is often observed [3,5]. Twinning-Induced Plasticity (TWIP) in combination with TRIP occurs in higher SFE steels [6]. The general trend is that with increasing SFE the following sequence of predominant deformation mechanism is observed: TRIP $\gamma \rightarrow \varepsilon \rightarrow \alpha'$, TRIP $\gamma \rightarrow \alpha'$, TWIP and slip [3,5–7].

The amount of α′-martensite formed during straining has important implications on the formability during cold forming processes [8,9]. During forming, parts of the components are subjected to uniaxial strain paths or more complex loading states. How the loading state influences the transformation characteristics has been addressed in a few studies but remains inconclusive. It has been reported for 304 steels that a biaxial tension enhances the martensitic transformation [10,11]. However other reports on 201, Fe18Cr10Ni (at low temperature) and 301LN steels show that uniaxial loading produces more martensite than biaxial loading [12–15]. The majority of the above mentioned studies were conducted on punched sheet samples where different locations exhibit different loading states, including uniaxial and equibiaxial tension. Microscopic observations have suggested that an increased density of dislocations under biaxial loading results in higher amount of martensite [13]. A detailed understanding of the role of the loading state is however missing.

Transformation kinetic models have helped in understanding the matter, but several points remain unclear. Some models suggest that a higher triaxiality factor Σ, i.e. the ratio of hydrostatic stress and the Von Mises stress, leads to a higher amount of formed martensite [16,17]. Such models predict that when e.g. loading equibiaxially (i.e. $\Sigma = 0.67$) will result in a higher amount of martensite than when loading uniaxially (i.e. $\Sigma = 0.33$). On the other hand, a recent kinetic model suggests that the fraction of strain-induced martensite does not only depend on the triaxiality factor but also on the Lode angle parameter: if this is the case, uniaxial loading produces more martensite than equibiaxial, as is for example observed for 301LN steel [14]. The above-mentioned kinetic models consider solely the mechanics of plasticity and phase transformations, do not consider microstructural properties such as for instance the evolving crystallographic texture during

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loading and cannot explain the dependence of the intermediate ε-martensite on the strain path.

In the present study we address the effect of loading state on the transformation behavior of a low SFE austenitic stainless steel exhibiting the γ → ε → α′ transformation sequence. A commercial 201 stainless steel is employed having a mean grain size of 45 μm and a nominal composition of Fe-16-18Cr-5.5-7.5Mn-3.5-5.5Ni-max1Si-max0.15C (wt%), which according to the empirical relationships of Ref. [18,19] has a SFE ~20 ± 3 mJm^{-2}. Cruciform-shaped and dogbone samples were deformed (both uniaxially and cruciforms equibiaxially) during neutron diffraction allowing the observation of ε- and α′-martensite evolution. The cruciform geometry was optimized with the aid of FE analysis using ABAQUS, the employed geometry is shown in the supplementary material S1a.

In situ neutron diffraction tests were carried out at the POLDI beamline of the Swiss neutron spallation source SINQ which is equipped with a biaxial machine and a tensile machine [20,21]. A schematic of the experimental setup is shown in the supplementary material S1c. The in-plane strain was measured with a 2-camera digital image correlation (DIC) system (GOM, Aramis 5M). Uniaxial loading (hereafter referred as UN) and equibiaxial loading (hereafter referred as EQ) were performed with a loading rate of 80 N/s. The uniaxial loading direction F2 was parallel to the rolling direction, RD, of the sheet (see supplementary material S1b), the equibiaxial load was performed along RD and TD. A uniaxial test was performed on a dogbone-shaped specimen (see supplementary material S1b) and the results were consistent with the UN cruciform sample. Neutron diffraction measurements were carried out in predefined force intervals upon interrupting the loading and holding the displacement until the sample was fractured. The maximum equivalent strain that could be reached during the equibiaxial test was ~16%, a limitation caused by the stress concentrations at the cross-arms of the cruciform specimen. The maximum strain reached under uniaxial tension was 29%. The neutron diffraction data were analyzed with the open source software Mantid [22].

EBSD studies were carried out on the as-received and on the deformed material. For the latter, additional samples were deformed uniaxially (dogbone) and equibiaxially (cruciform) up to 13% equivalent strain in order to obtain samples at comparable strains. The samples were ground with 1200 grit SiC paper and then electropolished for 5 s with a 16:3:1 (by volume) methanol, glycerol and perchloric acid solution. A field emission gun scanning electron microscope (FEG SEM) Zeiss ULTRA 55 equipped with EDAX Hikari Camera operated at 20 kV in high current mode with 120 μm aperture was used. The EBSD raw data were post-processed using the EDAX OIM Analysis 7.3 software.

The evolution of the neutron diffraction patterns during deformation is shown in Fig. 1a and b for the UN and EQ samples respectively. Initially only austenite reflections are observed. After ~10% strain (which corresponds to a true stress value of ~645 MPa, obtained from the dogbone sample) a reflection corresponding to ($10\bar{1}1_{\varepsilon}$) ε-martensite appears in the UN sample. The $110_{\alpha'}$ α′-martensite reflection appears only after 23% strain, which corresponds to a true stress value of ~1000 MPa, obtained from the dogbone sample. The increase in the α′ intensity is accompanied by a decrease in the intensity of ε, as can be observed in Fig. 1c where both reflections are compared at 20% and 29% strain. On the other hand, no reflections corresponding to ε- or α′-martensite are observed for the EQ sample up to 16% equivalent strain. A comparison of the neutron diffraction patterns at ~16% equivalent strain is given

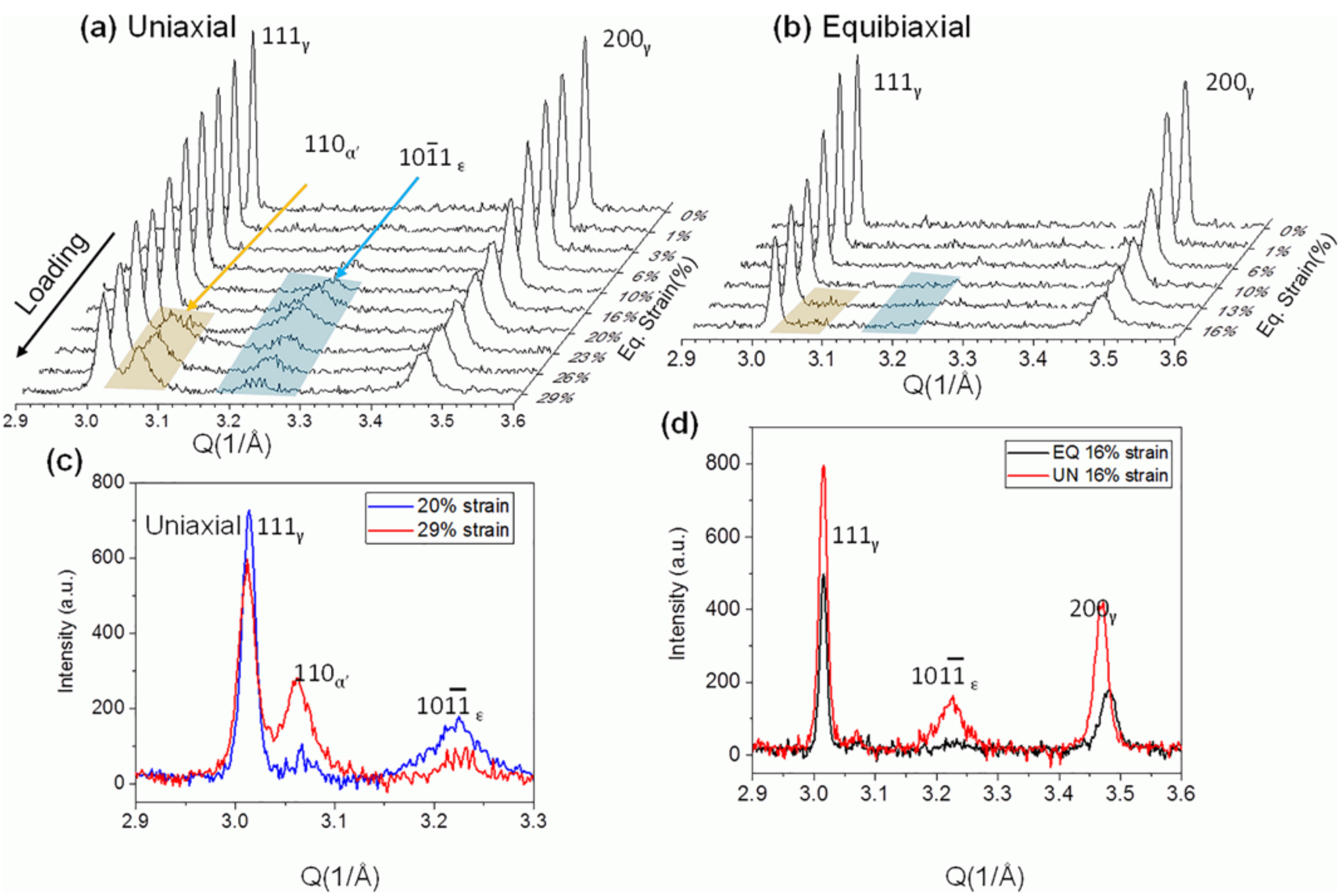

Fig. 1. Neutron diffraction patterns with increasing the applied strain for (a) uniaxial loading and (b) equibiaxial loading. (c) Comparison of the diffraction patterns at 20% and 29% equivalent strain for the UN sample, showing the increase of α′-martensite fraction in expense of ε-martensite. (d) Comparison of the diffraction patterns from the UN and EQ samples at 16% equivalent strain.