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A study on cyclic deformation response and dislocation structure evolution during extreme low cycle shear fatigue of a TRIP steel

Dayong An*, Stefan Zaefferer

Max-Planck-Institut für Eisenforschung GmbH, Max-Planck-Straße 1, 40237 Düsseldorf, Germany

Abstract: Shear fatigue of a TRIP steel under displacement control has been performed in this study. Electron channelling contrast imaging (ECCI) and cross-correlation based high resolution electron backscattering diffraction (CC-EBSD) have been applied to study the fatigued structure evolution combined with the residual stress and strain information. The fatigue dislocation structures are found to be closely related to the Taylor factor with a certain range of the Taylor factor being particularly influential. For those grains with sensitive Taylor factors, strong hardening associated with a high dislocation density are observed within the first 10 cycles. Areas with high dislocation density (walls, cells) and with low density (channels) become more evident after prolonged cycling (50 cycles). Furthermore, dislocation walls and cells become denser and thinner after 100 cycles. In contrast, for those grains with non-sensitive Taylor factors, planar structures remain even after 100 cycles. The cyclic deformation response can be considered as the result of dislocation structure evolution in grains with different Taylor factors. In addition, we find a close relationship between the dislocation structure and the inter- and intra-granular back stresses detected by CC-EBSD.

1. INTRODUCTION

Austenitic steels with transformation-induced plasticity (TRIP) exhibit a good combination of strength and ductility under monotonic deformation [1], while their fatigue behaviour has been rarely studied. Nevertheless, many of the TRIP steels are used for the automotive applications, where they undergo cyclic deformation during the service life [2]. Understanding the evolution of microstructure is, therefore, essential to make accurate prediction on fatigue life of these components [3]. It was reported that the dislocation structures changed already significant during low cycle fatigue (LCF) [4]. Therefore, in this study the cyclic deformation response combined with dislocation structures evolution during LCF is comprehensively investigated.

2. EXPERIEMENTAL PROCEDURES

The chemical composition (in wt. %) of the studied material is Fe-17.41Mn-1.503Al-0.287C. The materials were strip casted, homogenized at 1150°C for 2 h and quenched. Thereafter, 50% cold rolling and recrystallization annealing (900°C for 20 min) were performed on the studied material. The final specimen showed a fully austenitic structure with an average grain size of 13.7 μm. From the material shear samples with a geometry as shown in Fig. 1a were cut. They were grinded from 220 grit to 1000 grit SIC paper and then mechanical polished with 1μm diamond suspension. In order to obtain a high surface quality, the surface was finished by polishing with a 50 nm colloidal suspension of SiO_2 (OPS). Before shear fatigue, electron backscattering diffraction (EBSD) scan was performed to obtain the orientation information of the investigated grains. Shear fatigue with a digital image correlation (DIC) set-up was performed at room temperature with a tensile-compression instrument (Kammrath & Weiss GmbH, Dortmund, Germany) under displacement control (±60 μm). Fig. 1b shows an example of a DIC snapshot of the major strain distribution at the maximum tension position (+60 μm).The cyclic deformation response was characterized by the maximum tensile stress. Electron channelling contrast imaging (ECCI) was performed to observe the dislocation structure evolution after 0, 10, 30, 50, 100 cycles. After fatigue testing, cross-correlation based high resolution EBSD (CC-EBSD) [5] was applied to measure the residual strain and residual stress information of the fatigued grains.

* Corresponding author. E-mail: d.an@mpie.de, telephone: +49 211 6792 311.

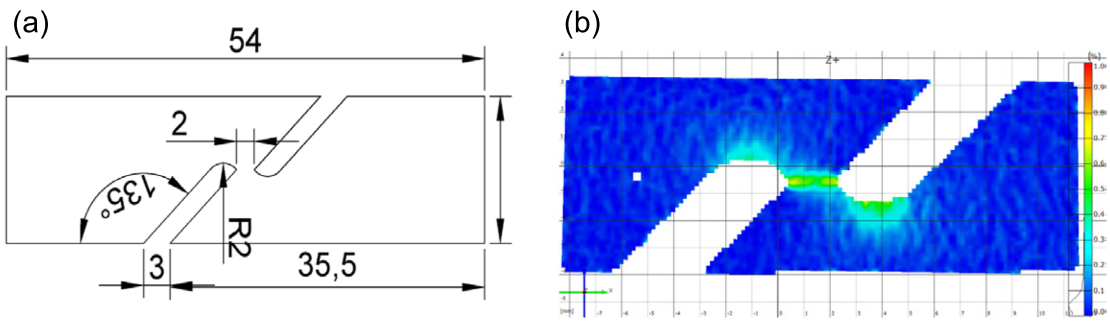

Fig. 1 (a) Geometry of the shear test specimen, in mm; (b) one digital image correlation (DIC) snapshot of the major strain distribution.

3. RESULTS AND DISCUSSION

3.1. Cyclic deformation response and related dislocation structure

Fig. 2 shows the maximum cyclic stress response in dependence of the number of load cycles. Strong cyclic hardening is observed from 0 to 10 cycles. After recrystallization annealing, ECCI results show that the grains are almost free of dislocations. However, dislocation densities have increased significantly after 10 cycles, as shown in Fig. 3. The dislocation structures are found to be closely related to the Taylor factor of the grains. Dislocation tangles or even wall structures are observed in grains with Taylor factor between 3.5 and 4, which is called as the sensitive value, which is a regime with an optimum number of slip systems allowing for easy interaction between slip systems. In contrast typical planar dislocation arrays are frequently found in grains with Taylor factor below 3 or larger than 4. The cyclic hardening rate become slow from 10 to 30 cycles, followed by a plateau stage until 50 cycles. Compared to the first 10 cycles, perceptible difference of dislocation structures can barely be observed in grains with sensitive Taylor factors after 30 cycles. In contrast, tangled bundles are formed in the grains with less-sensitive Taylor factors. During this stage, the weak cyclic hardening can be attributed to an increase of dislocation density in grains with less-sensitive Taylor factors. From 30 to 50 cycles, the total dislocation densities do not show big differences. It should be noted that the high-density dislocation structures (walls, cells) and the low density structures (channels) in sensitive grains become more evident after 50 cycles. Surprisingly, a trivial decrease of strength is found from 50 to 100 cycles, indicating a slight cyclic softening. One possible explanation for this is that dislocation walls become denser and the width of dislocation-free channels increases after prolonged cycling. Hence, the mean free path for dislocation movement during reverse loading becomes larger, leading to a decrease of the maximum tensile stress response. In addition, stacking faults (SFs) with long width are more frequently observed after 100 cycles, as illustrated in Fig. 3. In summary, the cyclic deformation response can be considered as the result of dislocation structure evolution in grains with both sensitive and non-sensitive Taylor factors.

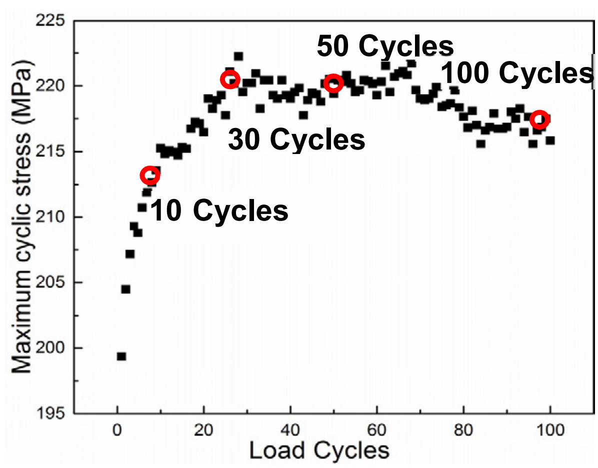

Fig. 2 Cyclic deformation response of the studied material against load cycles.

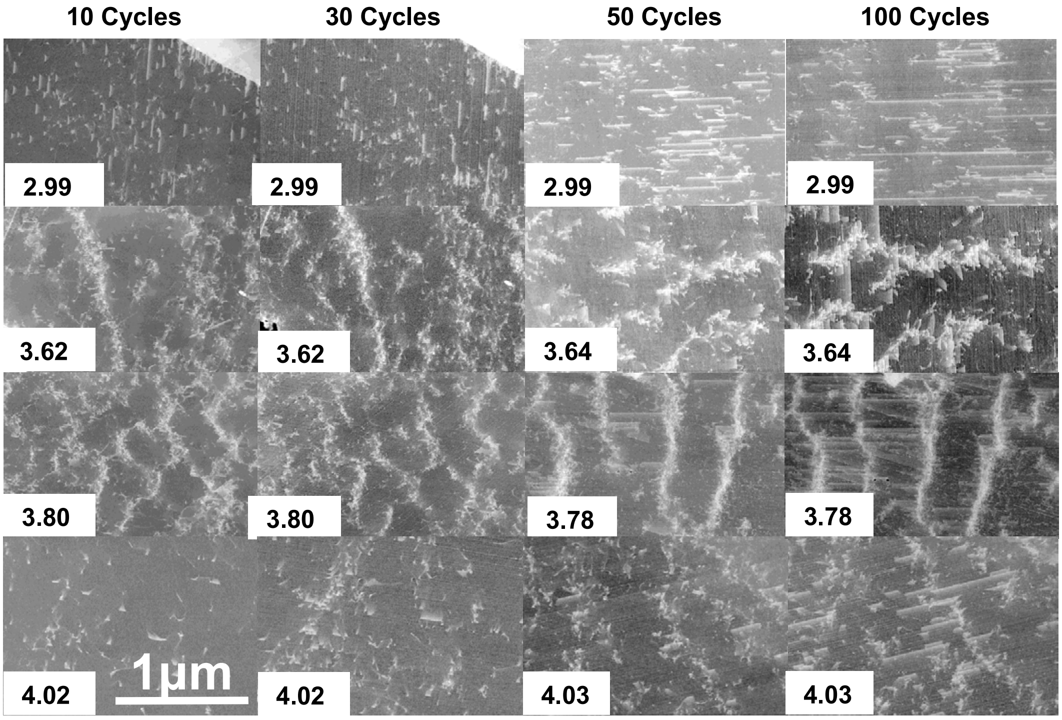

Fig. 3 Dislocation structures of grains with different Taylor factor after 10, 30, 50 and 100 cycles. The grains selected from 10 to 30 cycles are different from those selected from 50 to 100 cycles.

3.2. Residual strain and stress

CC-EBSD has been performed on the fatigued samples after 100 cycles. Fig. 4 shows one CC-EBSD result of a fatigued grain with Taylor factor of 3.78 under a strain amplitude of around 0.5%. ECCI images in Fig. 4 shows clearly the formation of dislocation walls and channels. In the elastic strain component maps red colour corresponds to tensile strain and blue corresponds to compressive strain. It can be seen that inside the dislocation walls compressive normal strains ε_{11} and ε_{22} prevail, while the normal strain ε_{33} as positive values. The high values of the shear components and von-Mises stresses at some of the boundaries indicate strain accommodation of differently deforming neighbouring grains [6].

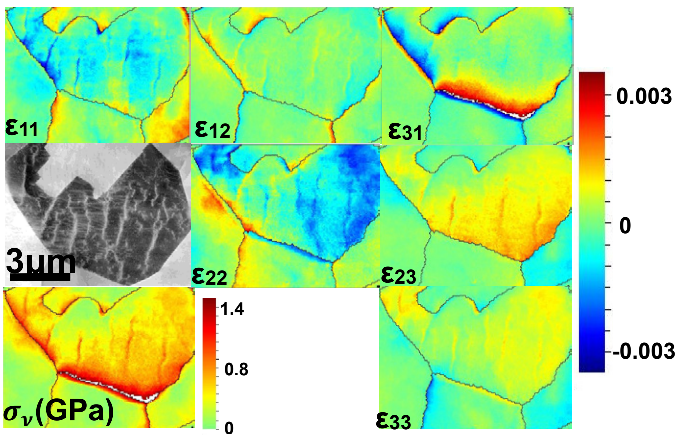

Fig. 4 Residual elastic strain and residual von Mises stresses as calculated by cross-correlation EBSD.

The distribution of von Mises stress (σ_v) is shown in the left bottom of Fig. 4. The areas corresponding to the dislocation wall centres are found to have appreciable higher stress values than the channels, which is called intra-granular back stress. It has been reported that the formation of regions of high or low dislocation density can relieve inter-granular back stresses but could also increase the intra-granular back stress due to the creation of strain incompatibilities between dislocation high/low regions [7]. In summary, the inter- and intra-granular back stresses are closely related to the dislocation structure and its evolution during cyclic straining.

4. CONCLUSION

In this study, displacement-controlled shear fatigue of a transformation-induced plasticity (TRIP) steel has been performed to investigate the cyclic deformation response associated with the dislocation evolution. Some conclusion can be drawn:

(1) The cyclic deformation response of the studied material during the first fatigue cycle (up to 100 cycles) can be characterized by four stages: a strong cyclic hardening stage (0-10 cycles), a weak cyclic hardening stage (10-30cycles), a plateau stage (30-50 cycles) and a weak cyclic softening stage (50-100cycles).

(2) The Taylor factor is proved to be a successful parameter to predict the dislocation structures in polycrystalline material. Dislocation structures in grains with low or high Taylor factors show a planar array structure. In contrast, complex dislocation structures (walls, cells and channels) are observed in grains with medium Taylor factor. We call this range the "sensitive Taylor factor range"

(3) The ddislocation density increases significantly at the beginning of fatigue (10 cycles). High-density dislocation structures (walls, cells) and low density structures (channels) become more evident after prolonged cycling. Furthermore, dislocation walls and cells become denser and thinner.

(4) Cross-correlation high resolution electron backscatter diffraction (CC-EBSD) has been performed to measure the residual strain and stress distribution in the fatigued grains. Intra-granular back stress can be observed on the places corresponding exactly to dislocation walls. Furthermore, grain boundary effect on strain and stress distribution are also detected.

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