Strain localization in <111> single crystals of Hadfield steel under compressive load

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Abstract. A study of strain localization under compression of <111> Hadfield steel single crystals at room temperature was done by light and transmission electron microscopy. At ε<1%, macro shear bands (MSB) form that have non-crystallographic and complex non-linear habit planes and are the results of the interaction of dislocation slip on conjugate slip planes. Mechanical twinning was experimentally found inside the MSB. After the stage of MSBs formation, deformation develops with high strain hardening coefficient and corresponds to interaction of slip and twinning inside as well as outside the MSBs.

1. Introduction
Hadfield manganese steel is well known for its anomalous high work hardening, ductility, and strength [1–3]. It has austenitic structure (FCC) and low stacking fault energy (γ=23mJ/m²) for a nominal composition of Mn 12-14 wt.% and C 1.0-1.3 wt.%. This combination makes steel successful for industrial applications such as impact hummers, railroad frogs, etc. The polycrystalline Hadfield steel is well-studied, but scientists have not got a single meaning on its hardening mechanism.

In the recent works, Hadfield steel single crystals were studied well under tension, and unusual strain hardening of this steel was attributed to pronounced twinning and strain ageing phenomenon [4,5]. The present paper examines the deformation macro- and microstructures of the <111>-oriented single crystals of Hadfield steel under compressive load to provide further development of our knowledge about their deformation mechanisms under different strain paths.

2. Methods
The material used in this study was the austenitic Hadfield steel with a composition of 13%Mn, 1.0%C in weight and Fe balance. The single crystals were grown by Bridgman technique in a He atmosphere. They were then homogenized for 24 h at 1373K. Electro-discharge machining was utilized to cut regular parallelepiped specimens with nominal dimensions of 4×4×7 mm. All specimens were mechanically ground, chemically etched to remove damaged surface layer. They then were solution-treated and water-quenched from 1373K after 1h. Before testing all samples were electrolytically polished. The compression test was performed with electromechanical Instron 3369 test machine at room temperature and a strain rate of 1.2×10⁻³ sec⁻¹. Experiments were repeated on five companion specimens to check repeatability. Olympus GX-71 microscope was utilized for optical analysis. For TEM investigations, the foils were prepared by mechanical grinding and jet electropolishing. Microstructure was examined in Philips CM 30 and Philips SEM 515 electron microscopes.
3. Results and Discussion
The microstructure and texture evolution of Hadfield steel under tension and compression at room temperature are determined mainly by mechanical twinning intensity and by a number of operating twin and slip systems [1-5]. The initial deformation mechanism of Hadfield steel single crystals of all orientations is slip, but it changes fast to twinning as the Hadfield steel possesses low stacking fault energy and high level of plastic flow stresses due to high carbon content [4,5]. Plastic strain corresponding to slip-to-twin transition depends on crystal axis orientation, and, in case of compressive load, it has the smallest value (ε<0.5%) in the single crystals oriented close to <001>-direction. Under compression of <111>-oriented crystals, slip can be accompanied by twinning but, nevertheless, it has to be the basic deformation mechanism.

The experimental true stress-strain curve of the <111>-oriented single crystal as presented in Figure 1 clearly indicates both a non-monotonic increase in stress during straining and non-homogeneous deformation of a specimen. The first part of the stress-strain curve, up to the strain of 15%, represents the work-hardening stage with serrated flow, stress drops and low strain hardening coefficient of θ=dσ/dε=800MPa. Stress drops are associated with the development of macroscopically visible shear bands (Fig. 1 a,b). After moderate strain, i.e. at the end of macro shear bands (MSB) formation, these bands occupy practically the whole volume of the crystal (Fig. 1 c). The second part of stress-strain curve is smooth, it has the high strain hardening coefficient of 1800MPa and is associated with deformation both inside and outside of MSBs.

An appropriate model for MSB boundary nucleation under multiple slip due to the formation of Lomer-Cottrell locks is proposed in previous papers [6,7]. On the basis of this model and our own experimental data, we assume the following stages of the <111> single crystals deformation. First, very low strains are controlled by multiple slip, as the <111> orientation is highly symmetrical one and the slip has homogeneous character (without pile-ups) [5]. The interaction of dislocations gliding on intersecting planes produces continuous non-crystallographic surfaces which consist of Lomer-Cottrell locks. These surfaces form habit planes for subsequent MSBs and do not coincide with {111}-type planes that are slip planes of fcc materials (Fig. 2a).
The macroscopically observed broad bands of 20-300 µm (Figs. 1a,b; 2b) do occur in all specimens after the plastic strain of $\varepsilon > 0.5\%$ and coincide with periodic stress relaxations. The decrease in stress (stress drop) is determined by softening mechanism inside the band due to lattice reorientation. The intensive slip inside MSBs causes crystal lattice rotation up to 10º compared to the matrix region as revealed by EBSD analysis. Both slip (Fig. 2 c) and twinning were found (Fig. 2 d-f) inside the MSB. It means that the lattice reorientation makes twinning possible inside the band, and following increase

Figure 2. The micro- and macro structures of the MSB in compressed <111> single crystal: (a) SEM micrograph of slip lines on the MSB boundary, $\varepsilon = 11.6\%$; (b) optical image of single crystal face side after repolishing and etching, $\varepsilon = 11.6\%$; (c,d) TEM bright field images showing dislocation structure and micro twins inside of the MSB, foils were cut in parallel with the MSB macrohabit plane, $\varepsilon = 5\%$; (e,f) TEM dark field image obtained in twin reflex and SADP to (d,e);
in stress after each drop is related to the interaction of slip and twinning inside the band. So, the inner structure of the band is getting stronger than that of surrounding material regions, and the next MSB forms. Although the curve is not smoothed, the amplitude of jerky flow is only a small fraction of the stress level. The stress oscillations cease at strain of 15%, and further deformation occurs in the whole specimen. This process can be easily observed both by optical microscopy and SEM.

No strain localization into MSBs has been found under compression of the Hadfield steel single crystals oriented along other crystallographic orientations (for instance, <001>, <123>, <011>) as twinning or single shear deformation starts from the very beginning of plastic flow. Moreover, change in type of dislocation structure from homogeneous dislocation distribution to planar dislocation configuration suppresses the MSB formation as it is observed during compression of the <111>-oriented specimens of Hadfield steel alloyed with aluminum. This also confirms the hypothesis that, for well-developed MSBs which form during compression in Hadfield steel single crystals, the multiple homogeneous slip is necessary.

4. Conclusions
In the present paper, <111> single crystals of conventional Hadfield steel (Fe-13Mn-1.0C, wt.%) were studied in order to shed light on the mechanisms of MSB formation under compressive load. The results obtained may be summarized as follows:

1. Shear banding is closely related to the structural anisotropy of pre-existing deformation mechanism. It is preceded by the formation of persistent non-crystallographic (shear habit plane is not a {111} plane) boundaries due to gliding dislocation interactions (Lomer-Cottrell locks). Formation of shear bands is strongly assisted by multiple slip, whereas, twinning, single slip or microlocalization (pile-ups of dislocations) will suppress MSB formation.

2. Rotation-induced mechanical instability within MSB leads to local reorientation of crystal lattice inside of the band and favors mechanical twinning in it.

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