Study of work-hardening behavior of high manganese steel during compression

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Abstract

High manganese steels are well used for their excellent hardening properties. In this study, we investigate the mechanical responses of high manganese steel in a compressed condition. During compression deformation, twin crystal is first generated inside some of the grains with orientation advantage, and then all of the grains are twinned. Selective twinning on some grains leads to the formation of textural structures. When the plastic deformation is low, twins appear independently and throughout the grain. After the true strain is more than 0.5, the twins appear as many small parallel short bars. Dislocation density does not increase significantly at the beginning of plastic deformation but increases rapidly while the flow stress no longer increases. Simultaneously, the twinning and the increased density of dislocations increase hardness, with a maximum value of 630 HV at a true strain of 0.6, during plastic deformation.

1. Introduction

Austenitic high-manganese steel with 15–25 wt% manganese content is characterized by excellent mechanical properties owing to its exceptional work hardening capacity. The extraordinary mechanical properties of this class of steels have been subject to several studies, many of which revealed that the high work-hardening behavior is related to the obstruction of dislocation movement during plastic deformation. Additional deformation mechanisms, such as stacking faults, dynamic strain aging (DSA) [1–3] and interaction of twins, have been observed in deformed steel to provide obstacles against dislocation motion. However, more than one type of mechanism occurs in plastic deformation and makes it difficult to distinguish between the hardening mechanisms’ relative contributions.

The deformation mechanisms and mechanical properties of face-centered cubic (fcc) metals are related to their stacking fault energy (SFE) [4], which would determine the slip of dislocation [5]. With a lower SFE, partial dislocation slip, mechanical twinning, and eventual transformation into hcp ε-martensite and/or bcc/ bct α’-martensite [6] occur when deformation while the perfect dislocation slips with a higher SFE. SFE values of 20 mJ m$^{-2}$ were the upper limits for ε-martensite, while twin formation would occur for SFE values between 12 and 35 mJ m$^{-2}$ or 14 and 50 mJ m$^{-2}$. For materials with SFE $>50$ mJ m$^{-2}$, the formation of twinning was strongly suppressed, and microbands are formed by planar glide in order to accommodate plastic deformation. Otherwise, The loading modes [7], temperature [8], grain size [9, 10], grain orientation [11] and strain rate, all can influence the activation of deformation twinning [12, 13].

Numerous studies have investigated the work-hardening behavior of high manganese steels during tensile deformation, but little work has been reported during compression. The present work aims to study the deformation behavior during compression of high manganese steel. Therefore, a detailed analysis of the microstructure evolution was carried out.
2. Experimental methods

The chemical composition of the investigated high manganese steel was Fe-20.16Mn-1.37C-0.09Nb-0.0153V (wt%) as determined by wet chemical analysis. The material was melted in an induction furnace and cast into a 12 kg ingot. In order to homogenize the material and remove segregation zones origination from solidification, the cast ingot was reheated to 1200 °C for 30 min and hot forged into plates that are 15 mm thick and 60 mm wide. Bar-shaped samples (15 × 15 × 60 mm) were cut from the hot-forged ingot and solution treatment for 60 min at 1100 °C and subsequently quenched in water. Cylindrical compression test samples were machined from the bars with gage dimensions of 5 mm diameter and 10 mm length. Compression tests were carried out at room temperature with a 1 mm min \(^{-1}\) compressed rate. Six specimens were set up for compression testing and stopped compressing when they reached a predetermined compression rate. The predetermined compression rate was 1 mm, 2 mm, 3 mm, 4 mm, 5 mm and 6 mm, while the true strain for each specimen was 0.11, 0.22, 0.35, 0.51, 0.69 and 0.91.

After compression, the deformed samples were tested by XRD (x-ray diffraction). Before the test, the surface stress was removed by electrochemical polishing. The polishing fluid was a 10% perchloric acid alcohol solution, and the current density during polishing is 5 A cm \(^{-2}\). The diffraction angle range detected by XRD was 40–120°, and the anode target was Cu. The specimens were sand polished and corroded using a mixed aqueous solution of HCl and K2CrO4, then the microstructure was observed using Leica and ZEISS Gemini SEM 500 Scanning Electron Microscope.

Electron backscatter diffraction (EBSD) measurements were carried out on a FEIQUANTAFEG450 equipped with a Hikari attachment. Transmission electron microscopy (TEM) was performed on a TECNAI F20. Thin foils were obtained by ion thinning.

3. Result

3.1. Microstructure of as-fabricated material

Plenty of carbides is distributed on the grain boundaries after hot forging in the microstructure of the high manganese steel shown in figure 1. The average grain size was 49.4 μm by performing a line intercept. While the carbide along the grain boundaries was dissolved and the grains grew to 118.4 μm after heat treatment. However,
some carbides within the matrix do not dissolve by solution treatment. Black dots appear in figure 1 due to carbides drop-out after erosion.

3.2. Compression properties and XRD

The measured flow stress curve is given in figure 2. The compression process can be divided into three stages according to the change in the true stress of the deformation. The true stress curves for all three steps are linearly related. The first stage undergoes elastic deformation and obeys Hooke’s law. Work hardening occurs in the following stages, and the true stress increases linearly with increasing true strain. This period will last till the true strain reaches about 0.75, and the slope of the true stress starts to decrease at the end of this period. Subsequently, the value of the true stress hardly changes anymore in the last stage of the compression test, and the deformation stress reaches a maximum. The hardness values of the deformed specimens are also presented in figure 2. The hardness also has a tremendous increase due to the occurrence of deformation. The increase in hardness is relatively fast at the beginning and then decreases. The hardness of the original sample is 200 HV and can be up to 680 HV when the true strain is at 0.96.

XRD tested the sample with different deformation rates, and the result is shown in figure 3. FCC austenite phase ($\gamma$) was confirmed as the matrix phase and did not transform during compression. As shown in figure 3, as the deformation rate increases, almost all diffraction intensity decreases but $\gamma$-(220). The diffraction intensity of $\gamma$-(220) hardly changes during deformed.
The twinning can effectively block dislocation slip and reduce the mean free path of dislocation, resulting in a large number of dislocation pileups and a dynamic Hall-Peach strengthening effect. The density of dislocation can rise during plastic deformation. It can be the dislocation density can be calculated from the peak position and full width at half maxima (FWHM) of (111), (200), (220), (311), (222) and (400) at the different samples with various compression rate by use of the Williamson-Hall equation [14, 15].

\[
\frac{\beta \cos \theta}{\lambda} = \frac{0.9}{D} + 2\frac{\sin \theta}{\lambda}
\]

\[
\rho = 16.1 \left( \frac{\varepsilon}{b} \right)^2
\]

Where \(\theta\) is the diffraction angle of the peak, \(\beta\) is the FWHM of the peak, \(\lambda\) is the wavelength of the incident x-ray beam (0.15406 nm), \(D\) is the crystallite size, \(\varepsilon\) is a heterogeneous train, and \(b\) is the magnitude of the vector (0.2552 nm in the present material), respectively. The dislocation density of samples with various compression is plotted in figure. Dislocation density does not increase significantly until the deformation reaches 4 mm and increases rapidly to \(11 \times 10^{16} \, \text{m}^{-2}\). After compression, the dislocation density is about ten times the beginning of the compression.

### 3.3. Microstructure evolution during compression

The microstructure of high manganese steel is shown in figure 5. Parallel deformation bands only appear within some grains, and the bands in some areas intersect in a web-like pattern. Furthermore, the deformation bands start to be present inside more grains as the true strain increases. It can be observed that deformation bands can be observed inside almost all grains after the true strain reaches 0.35. However, the deformation bands are no longer clearly observable when the deformation amount continues to increase.

The IPF map of the sample with a true strain of 0.11 is shown in figure 6. The deformation bands are generated only in crystals of a specific orientation. The angle of interface between the matrix and the deformation zone is 60°, which means that twins are generated by plastic deformation. It can be seen that the twins run through the grains, but the width of the twins varies at different positions. The width of the twin near the grain boundary is smaller, while the twin inside the grain is wider. However, the use of EBSD on highly deformed high manganese steel is not satisfactory. In order to study the microstructural evolution of high manganese steel under larger deformation, transmission electron microscopy was used to observe its morphology.

The TEM micrograph of the specimen with a true strain of 0.51, 0.69 and 0.91 is shown in figure 5. Twin crystals were observed in the specimens, and the greater the strain, the more twins appeared. When the true strain is 0.69 or 0.91, the twin crystals are arranged parallel to each other, and their disappearance is in a straight line. However, they are not secondary twins according to the diffraction spots.

### 4. Discussion

The active deformation mechanisms in TWIP steels depend on the SFE [16], which, in turn, varies with its chemical composition and grain size. SFE increases with the content of carbon and manganese. The SFE of steel...
Figure 5. Microstructures at different level of compression (a) $e = 0.1$ (b) $e = 0.2$ (c) $e = 0.3$ (d) $e = 0.4$ (e) $e = 0.5$ (f) $e = 0.6$.

Figure 6. IPF map of the specimen with a true strain of 0.11 (a) the twin occur at some grains with advantage orientation and (b) the angle of twin boundaries is 60°.
with such a composition is 35–40 mJ m\(^{-2}\). Twinning would occur complying with Schmid law at small strain. The dependence of activation of deformation twinning on the Schmid factor and strong rotations of grains leads to the difference in intensity of diffraction peaks of various grain families. The twinning usually occurs in (111) (110) rotation during tension while occurs in (100) during compression. Non-uniform deformation on

**Figure 7.** TEM images taken from the sample deformed to true strain of 0.51 (a) and (b), 0.69 (c) and (d), and 0.91 (e) and (f). (a), (c) and (e) are bright field images. (b), (d) and (f) are dark field images.
different grains result in textures. The main textures of high manganese steel after compression or rolling are Goss texture \{011\} (100) and Brass texture \{011\} (211) \[11, 17, 18\]. The texture would turn from Goss texture to Brass texture when the strain is 0.4 to 0.6 \[19, 20\]. That is why the intensity of diffraction peaks of \{111\} and \{200\} decrease but the intensity of diffraction peak of \{220\} increases at the beginning of compression, reverse after the true strain exceeds 0.51.

Plastic deformation is related to the movement of dislocations. The resistance to dislocation motion is an essential factor affecting the resistance to deformation. High manganese steel produces twins during plastic deformation, dividing the grain into several parts, thus obstructing dislocations and reducing the mean free path of dislocation. Therefore, the excellent behavior of hardening is related to twinning and dislocation. As the figure 4 shows, there was no significant increase in dislocation during the hardening period but increases rapidly in the ending deformation stage. Dislocations do not contribute much to increasing the flow stress, and the hardening effect mainly depends on the twinning \[21\]. Finally, the amounts of twins have reached its limit, the movement of dislocations is greatly restricted, and newly generated dislocations become the main form of continued plastic deformation. Twin crystals and dislocations are generated at different plastic deformation stages, increasing the hardness of high manganese steel.

The twinning behavior in high manganese steel has been explained using the Schmid factor distribution and Taylor factor distribution. The twinning occurs in some orientations easier, so twinning was firstly observed in the grain with such orientation \[22\]. However, there is a slight difference in orientation within the exact grain due to the coarse grain size of high manganese steel. The difference in orientation is especially prominent when there is internal stress \[23\]. The orientation dependence of twinning prevents twins from traversing different orientation directions, even for slight differences in orientation. It coincided with the twin distribution in figure 6. As the deformation increases, twinning occurs in other grains as well. The stress of deformation during the compression process follows the increase. Stress from deformation divides the grains into tiny regions with different orientations, resulting in shorter twinning later, as the figure 7 shown.

Twinning is accompanied by the decomposition of prefect dislocation and turns to a partial dislocation. It reduces dislocation accumulation and leads to not becoming a large volume quickly in the initial stage. However, dislocations increase rapidly and cluster on the grain and twin boundaries once the twin content reaches saturation.

5. Conclusion

In the present study, the microstructural features of high manganese steel during compression have been studied in detail. The main deformation mechanisms identified using XRD, EBSD and TEM were micro-twinning and slip. The twin was observed, and the dislocation density was calculated.

Twinning is selectively produced first at some grains, which have an advantage in the Schmid factor. Nevertheless, the twinning will happen in most grains during the compression. Dislocations are less likely to accumulate when the proportion of twins is small. It will grow explosively in the later stages of compression deformation. The twin and dislocation can increase the hardness of the high manganese steels.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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