Effect of manganese on work-hardening of as-quenched martensitic steels

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Lath martensitic steel is expected to be applied to automobile body structures. It is necessary to balance the strength and ductility to clarify the relation between microstructural factors and mechanical properties. Manganese is known to increase the work-hardening rate of lath martensitic steels. However, the reason for this has not been clarified yet. In this study, low-carbon lath martensitic steels with different manganese concentrations were observed by microscopy, served tensile tests, and strain distribution observations by the microscale digital image correlation analysis. The work-hardening rate of martensitic steel containing 8 mass% manganese was higher than that of martensitic steels containing 3 and 5 mass% manganese. When the macroscopic nominal strain was 0.01, in-lath slips were activated in martensitic steel containing 5 mass% manganese. On the other hand, out-of-lath slips as well as the in-lath slips were activated in martensitic steel containing 8 mass% manganese. Twins, called long twins, whose longitudes are the same as the longitude of laths exist in both martensitic steels containing 5 and 8 mass% manganese. Short twins that partially cross the lath were only observed in martensitic steel containing 8 mass% manganese. Because twin boundaries are high-angle boundaries, the short twins are supposed to prevent the development of in-lath slip deformation and promote out-of-lath slip deformation. This seems to be the mechanism of the higher work-hardening behavior observed in martensitic steel containing 8 mass% manganese.

Keywords: *lath martensitic steel, manganese, work-hardening, twin*

1. Introduction

Lath martensite is a microstructure of low-carbon martensitic steels. It is expected to be the base phase of next-generation automotive materials because its balance of strength and ductility is better. In addition, it is known that manganese increases the work-hardening rate of lath martensitic steels. As a result, the strength and ductility of lath martensitic steels concluding manganese are higher[1). However, the relation between the microstructure and mechanical properties of lath martensitic steels has not yet been clarified. In lath martensite, slips are classified into the in-lath slip and the out-of-lath slip. In-lath slip is a slip along the lath boundaries. Out-of-lath slip is a slip that crosses the longitude of the lath. Harjo et al.[2)] reported two types of microstructural components one of which is a hard-packet orientation component and the other is a soft-packet orientation component depending on their slip system. The hard-packet orientation component is considered to affect the work-hardening of lath martensitic steels.

The aim of this study is to clarify the relation between microstructural factors and the work-hardening behavior of the lath of lath martensitic steel including manganese.

2. Experiments

2.1 Specimens

Fe-0.1C-c_{Mn}Mn (c_{Mn} = 3, 5, 8 mass%) steels were hot and cold rolled after being cast in a laboratory. Those plates were austenitized at 950, 1050 and 1100 ^{o}C in argon gas and quenched into water.

2.2 Tensile test and observation of microscale strain distribution

The specimens were subjected to two types of tensile tests. One was a macroscopic-scale tensile test using spray paints, an optical microscope (Dino-LitePremier500M made by AnMo Electronics), and an Instron-type tensile testing machine (AG-10TA made by Shimadzu Corporation). In this test, the stress was measured by the load cell on the Instron-type tensile testing machine and the strain was calculated by digital image correlation (DIC) analysis software (VIC-2D made by Correlated Solutions) using the spray paints on the surface of the specimens for drawing stress-strain curves. The other was a microscopic scale tensile test using silver nano particles and a scanning electron microscope (SEM, Ultra55 made by Zeiss), electron backscatter diffraction (EBSD) analysis (DVC5 made by TSL) and an Instron-type tensile testing machine (AG-10TA made by Shimadzu Corporation). The strains calculated by the microscopic-scale DIC analysis were total strains because both ends of the specimens were fixed by the jigs.

2.3 Microscopic observation

The microstructures of specimens were observed using SEM (Scios made by Thermo Fisher Scientific), EBSD analysis (Symmetry S3 made by Oxford Instruments), and transmission electron microscopy (TEM, JEM-ARM200F made by JEOL).

3. Results

The work-hardening rate of Fe-0.1C-8Mn steel is higher than Fe-0.1C-3, 5Mn steels. As a result, the strength and ductility of Fe-0.1C-8Mn are enlarged.

Figure 1 shows the crystal orientation maps before the tensile test measured by EBSD analysis and the corresponding engineering total strain distributions parallel to the tensile direction measured by microscopic scale DIC analysis of Fe-0.1C-5Mn steel and Fe-0.1C-8Mn steel as-quenched at 1050 ^{o}C. The ovals H are areas where the strains parallel to the tensile direction develop along the

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longitude of the block. The authors selected randomly two blocks for Fe-0.1C-5Mn steel and three blocks for Fe-0.1C-8Mn steel as indicated in Figure 1. The slip systems having the highest Schmid factor in the block and engineering total strain parallel to the tensile direction are listed in Table 1. High strain concentrations were observed where the Schmid factors of the in-lath slip are the highest in blocks 1 and 3. The strain concentrations were low in blocks 2 and 4 where the Schmid factors of the out-of-lath slip were the highest. It is worth noting that high strain concentrations in blocks where the Schmid factors of the out-of-lath slip were the highest were observed only in Fe-0.1C-8Mn steel (blocks 5).

The microstructures of martensite observed by SEM and EBSD analysis were similar in Fe-0.1C-5Mn steel and Fe-0.1C-8Mn steel. The microstructures were fully lath martensite. And the volume fraction of the retained austenite in each steel was small.

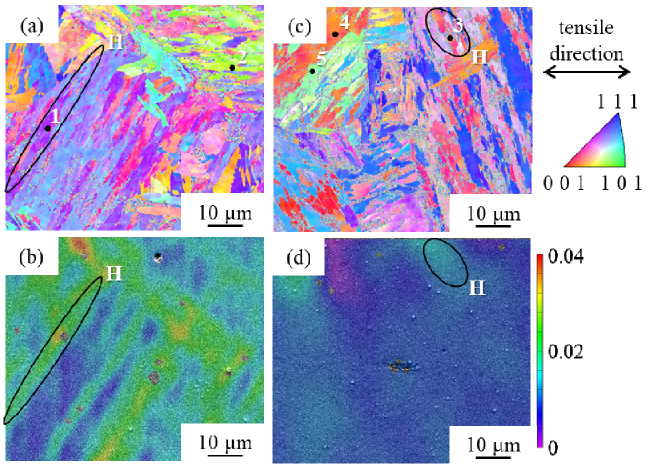

Figure 1 Crystal orientation maps measured by EBSD analysis obtained for Fe-0.1C-5Mn steel (a) and Fe-0.1C-8Mn steel (c) as-quenched at 1050 ºC before tensile deformation, and corresponding engineering total strain distributions parallel to tensile direction measured by DIC analysis obtained at a macroscopic engineering strain of 0.01 for Fe-0.1C-5Mn steel (b) and Fe-0.1C-8Mn steel (d) as-quenched at 1050 ºC. Numbers correspond to blocks in Table 1.

4. Discussion

The reason that the work-hardening rate of Fe-0.1C-8Mn steel is higher than Fe-0.1C-3, 5Mn steels is discussed. Retained austenite is known to increase the work-hardening rate of martensitic steels. However, in this study, the effects could be ignored because the amounts of retained austenite were small. It was considered from the results of the DIC analysis that there was more something to prevent in-lath slip and to promote out-of-lath slip in Fe-0.1C-8Mn steel than in Fe-0.1C-5Mn steel.

Two types of twins were observed in laths by TEM observation. Short twins that partially cross the lath are only observed in the Fe-0.1C-8Mn steel. The twins obtained by TEM have high-angle boundaries with the lath as the parent phase[3]. The short twins dividing the longitude of the lath are supposed to prevent the development of in-lath slip deformation and to promote out-of-lath slip deformation. This seems to be the mechanism of the higher work-hardening behavior observed in the Fe-0.1C-8Mn steel.

5. Conclusions

The following findings were obtained by the microscopic observation, the tensile tests, and the strain distribution observations of Fe-0.1C-c_{Mn}Mn (c_{Mn} = 3, 5, 8 mass%) martensitic steels.

(1) The work-hardening rate of the Fe-0.1C-8Mn steel is higher than that of the Fe-0.1C-3, 5Mn steels. As a result, the strength and ductility of the Fe-0.1C-8Mn are higher.

(2) The short twins observed in Fe-0.1C-8Mn steel are supposed to prevent the development of in-lath slip deformation and promote out-of-lath slip deformation since twin boundaries are high-angle boundaries. This seems to be the mechanism of the higher work-hardening behavior observed in the Fe-0.1C-8Mn steel.

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Table 1 Relationship between Schmid factor and engineering total strain parallel to tensile direction.

Specimen	Austenitized temperature	Block	Character of maximum Schmid factor	Engineering total strain parallel to the tensile direction
Fe-0.1C-5Mn	1050	1	In-lath	0.023
Fe-0.1C-5Mn	1050	2	Out-of-lath	0.008
Fe-0.1C-8Mn	1050	3	In-lath	0.015
Fe-0.1C-8Mn	1050	4	Out-of-lath	0.003
Fe-0.1C-8Mn	1050	5	Out-of-lath	0.013