Effect of aluminum addition on martensitic transformation in medium carbon steel

Yusaku Shirakami1, Takuro Masumura2, Toshihiro Tsuchiyama2, Shigenobu Nanba3

1Graduate school of Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
2Department of Materials, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
3Materials Research laboratory, Kobe Steel, Ltd., 1-5-5, takatsukadai, Nishi-ku, Kobe 651-2271, Japan

The effect of aluminum on the Ms temperature and microstructure of martensite was investigated in medium carbon steels with and without aluminum. The dilatometry test revealed that the Ms temperatures of 0 mass% and 2 mass% aluminum steels were estimated to be 568 and 638 K, respectively, and increased as the addition of aluminum. Although both steels comprise lath martensite structures, some blocks near the prior austenite grain boundary in 2 mass% aluminum steel are coarser than others. The Vickers hardness of 0 mass% and 2 mass% aluminum steels are 754 and 718 HV, respectively: the hardness decreases with the addition of aluminum. The 200 diffraction peaks in as-quenched 0 mass% and 2 mass% aluminum steel indicate that the solute carbon in martensite matrix decreases with promoting auto-tempering owing to increasing the Ms temperature. In conclusion, the formation of coarse blocks and the reduction of the solute carbon, which are due to the increase of Ms temperature, leads to the decreasing of hardness in aluminum-added steel.

Keywords: *martensite, microstructure, M_S temperature, auto-tempering, aluminum*

1. Introduction

Lath martensite in carbon steel is an important structure for strengthening steel. Recently, as-quenched martensite steel has been utilized to develop ultra-high strength steels of TS 1500MPa class and above, such as hot-stamped steel. On the other hand, because the as-quenched martensite has low toughness, it is unsafe to use as structural steels.

Martensite in carbon steel is obtained by rapid cooling from the austenite phase region to the martensite transformation start (Ms) temperature. If the Ms temperature is high enough to occur carbon diffusion sufficiently, the segregation of carbon, the precipitation of carbides, and the recovery of martensite during cooling (auto-tempering) should be occurred. In previous study, 3D atom probe tomography[1] and electrical resistivity measurement[2] revealed that the carbide precipitation and segregation of carbon to dislocations and grain boundaries were occurred in as-quenched martensite of carbon steel. Therefore, the microstructure and mechanical properties of as-quenched martensite are expected to be controlled by auto-tempering. If the low toughness of as-quenched martensite is improved, the industrial value of the process will be high because the ultra-high strength steel can be produced by a single heat process, which is expected to significantly reduce the costs. In this study, in order to change the degree of auto-tempering, the Ms temperature was varied through the addition of alloying elements.

Aluminum and cobalt are known to increase the Ms temperature[3]. In particular, aluminum is cheaper than cobalt and is a lightweight alloying element with about one-third the density of iron. In medium manganese steels, high manganese steels and austenitic stainless steels, there have been many studies on light-weight and low-density steels with 5~10 mass% aluminum addition to increase stacking fault energy and reduce weight[4]. However, there have been few studies on the effect of aluminum addition on the microstructure and mechanical properties of as-quenched martensite in carbon steel. In this study, the effect of aluminum on the Ms temperature and microstructure of martensite was investigated in the medium carbon steels with and without aluminum.

2. Experiment

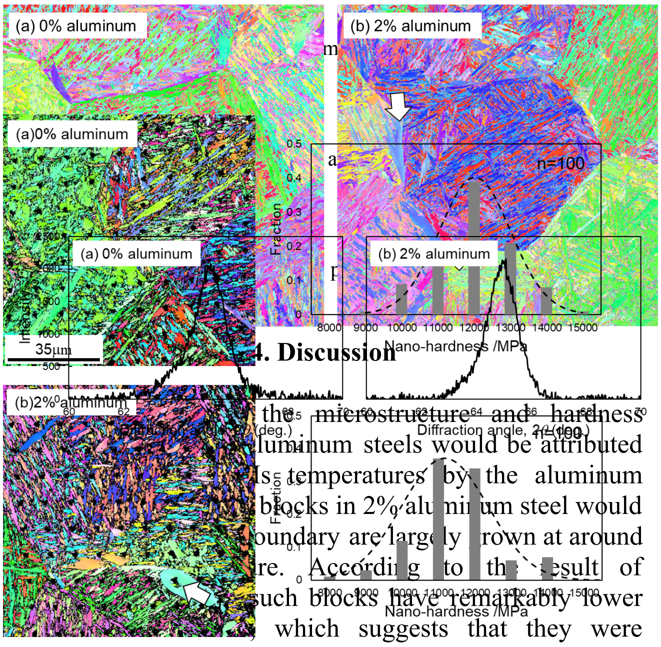
Fe-0.5%C-1.5%Mn-(0, 2)%Al alloys were used in this study (0% and 2% aluminum steels). These samples were hot-rolled at1473K to obtain the plates with a thickness of 5mm, and then solution-treated at 1273K for 30min (austenite single phase region) in argon atmosphere, followed by water cooling to obtain a quenched martensite microstructure. These specimens were subjected to dilatometry test, observation with an optical microscope, Vickers hardness test, nanoindentation test, electron back-scattering diffraction (EBSD), and X-ray line profile analysis.

Table 1 Chemical compositions of alloys used in this study(mass%).

	Al	C	Mn	N	O	Fe
0% aluminum	0.03	0.46	1.52	0.003	0.002	bal.
2% aluminum	1.93	0.46	1.42	0.004	0.003	bal.

3. Result

The Ms temperatures of 0% and 2% aluminum steels were estimated by dilatometry test to be 568 and 638K, respectively, and increased as the addition of aluminum. **Fig. 1** shows the crystallographic orientation maps of (a) 0% and (b) 2% aluminum steels. Although both steels comprise lath martensite structures, some blocks near the prior austenite grain boundary are coarser in 2% aluminum steel than others (as indicated by the arrow). The Vickers hardness of 0% and 2% aluminum steels are 754 and 718 HV, respectively: the hardness decreases with the addition of aluminum. **Fig. 2** shows the crystallographic orientation maps in the area tested by nano-indentation and the nano-hardness distribution of (a) 0% and (b) 2% aluminum steels. The average value of nano-hardness are 11557 and 10967MPa, respectively, indicating that the hardness is lowered by the addition of aluminum, which is corresponding to the result of Vickers hardness. Focusing on the distribution, it can be seen that the highest hardness is almost the same at approximately 14000MPa, while the 13000MPa class is significantly reduced in 2% aluminum steel. The nano-hardness distribution of 2% aluminum steel has also shifted toward the lower hardness side than that of 0% aluminum steel. Furthermore, the nano-hardness of a coarser block is 7832MPa (as indicated by the arrow), which is the lowest hardness. **Fig. 3** shows the 200 diffraction peaks in as-quenched (a) 0% and (b) 2% aluminum steels. The diffraction peak of 0% aluminum steel is clearly asymmetric, and a peak derived from the c-axis can be confirmed on the 63-64 degrees, which means martensite in 0% aluminum steel partially possesses the bct structure. On the other hand, the diffraction peak of 2% aluminum steel is nearly symmetrical, which means solute carbon content was reduced and c-axis has partially disappeared by auto-tempering. As a result, martensite of 2% aluminum steel exhibits nearly bcc structure.



4. Discussion

the microstructure and hardness ...luminum steels would be attributed ...Ms temperatures by the aluminum ...blocks in 2% aluminum steel would ...oundary are largely grown at around ...re. According to the result of ...such blocks have remarkably lower ..., which suggests that they were initially generated and promoted the segregation of carbon and precipitation especially. Not only them, since the average nano-hardness is lowered by addition of aluminum, solute carbon content in 2% aluminum steel is expected to be less than that in 0% aluminum steel with promoting auto-tempering due to increasing the Ms temperature. This would be presumed from the disappearance of c-axis in the diffraction profiles of 200 in 2% aluminum steel. It can be concluded that the addition of aluminum to medium carbon martensite leads to reduce solute carbon and results in an inhomogeneous hardness microstructure.

5. Conclusions

To control auto-tempering behavior by varying the Ms temperature, the measurement of Ms temperatures and microstructure characterization of martensite was carried out in medium carbon steels with and without aluminum. The results are summarized as follows:

(1) The Ms temperatures of 0% and 2% aluminum steels were estimated by dilatometry test to be 568 and 638K, respectively, and increased as the addition of aluminum.
(2) Both 0% and 2% aluminum steels comprise lath martensite structures, some blocks near the prior austenite grain boundary are coarser in 2% aluminum steel. Also, they have lower hardness than others.
(3) From the hardness decrease and the disappearance of c-axis in the diffraction profiles of 200 in 2% aluminum steel, it would be presumed that solute carbon content in 2% aluminum steel is less than that in 0% aluminum steel with promoting auto-tempering due to increasing the Ms temperature.

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