Quantitative Evaluation of the Effect of Cooling Rate on the Auto-Tempering in Martensitic Steels

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The hardness of martensitic steels increases with increasing carbon content due to the solid solution strengthening by carbon. However, in steels with high Ms temperature (C<0.4%), the hardness decreases due to auto-tempering after the martensite transformation. The degree of tempering can be quantitatively evaluated from the integrated diffusion area S (=ΣDt) where D is the diffusion coefficient of carbon in bcc-Fe and t is the holding time. True hardness HV* without the effect of auto-tempering is expressed by the equation;
HV* = 1.75 + 8.2 × (mass%C)$^{1/2}$. When the hardness of as-quenched martensite is HV, the standardized hardness Hs is expressed by
Hs =HV/HV*. It was confirmed that the equation: Hs=1.0-0.0052×{18+(logS)}^{2} is realized in the relation between S and Hs.   In this study, cooling curves were obtained at many points in a Jominy end-quench test piece and the S-values were calculated from the cooling curves for the temperature range below the M_{50} temperature. The calculated S-values give the hardness at each point in a Jominy end-quench test piece and the calculated hardness was compared with experimental data. As a result, it was found that significant decrease in hardness occurs within 1 mm from the quenching edge but the calculated hardness agrees well with the experimental data in the points far from the quenching edge more than 1mm.

1. Introduction

The hardness of quenched martensitic steel increases with larger amount of carbon contained in the steel. However, high-carbon steels (C > 0.6%) contain high quantities of retained austenite and decrease in hardness as the Mf temperature falls below room temperature. In addition, low-carbon steels (C < 0.4%) with high Ms temperature also decrease in hardness due to auto-tempering after martensitic transformation[1]. The degree of tempering up to 400ºC can be quantitatively evaluated by using the integrated diffusion area S (= ΣDt), where D is the coefficient of carbon diffusion in bcc-Fe and t is retention time[2]. Meanwhile, it can be assumed that the degree of auto-tempering varies depending on the cooling rate, as auto-tempering occurs during the cooling process immediately after martensitic transformation from quenching. In this study, we therefore used steels with carbon content of up to 0.6% to estimate the true hardness of the quenched martensitic steel that is not affected by auto-tempering, calculated the carbon diffusion area based on the cooling curve during quenching, and estimated the hardness of the martensitic steel after undergoing auto-tempering.

2. Materials and methods

For our experiments, we used commercially available carbon steels with different carbon contents (S25C, S35C, S45C, and S55C), and chromium-molybdenum steels (SCM420, SCM435, and SCM440). Table 1 shows the chemical compositions and transformation temperature of the steels. We set the sample size to 16 mm in diameter and 3 mm in thickness, and conducted quenching with solution treatment at 890ºC for 30 min in N_2 gas atmosphere, followed by cooling in cool 5% salt water. Next, we conducted tempering treatment on the quenched material within the temperature range of 200 to 600ºC for the heating period of 60 min. We conducted the Vickers hardness test on a cut surface (3 × 16 mm) that was cut under a load of 2.9 N. We took measurements at five points, and obtained the hardness of each test piece as the mean value of the five points. We measured the transformation temperature based on linear expansion during cooling (60º C/s [500 → 150ºC]) by using a high-frequency induction heating transformation temperature measuring system. There was a large temperature range (Ms temperature to Mf temperature) for the martensitic transformation of steel, and martensite that was formed just below the Ms temperature and one that was formed just above the Mf temperature both existed even in one former austenite grain[3], resulting in greatly varying degrees of auto-tempering. To level the degree of auto-tempering, we decided to use the M_{50} temperature, at which the volume fraction of martensitic transformation was 50%, in this study. We specified the size of a Jominy end-quench test piece as 25 mm in diameter and 100 mm in length, and measured the temperature by forming a hole with 1.1 mm diameter from the steel material surface at each position and fixing the sheathed thermocouple at the center of the test piece. As the conditions of the Jominy end-quench test, we specified the heating temperature as 845ºC for 0.5 hours, and conducted water jet cooling on one end according to JIS G 0561. We evaluated the hardness of the Jominy end-quench test piece by the Vickers hardness test, by vertically cutting the piece in the axial direction and applying the load of 2.9 N at the center of the diameter at each position from the cooling end of the cut surface (25 × 100 mm).

3. Results of experiments

3.1 Changes in hardness due to tempering

Figure 1 shows the relationship between the carbon diffusion area due to tempering and Vickers hardness of chromium-molybdenum steel. It shows that hardness
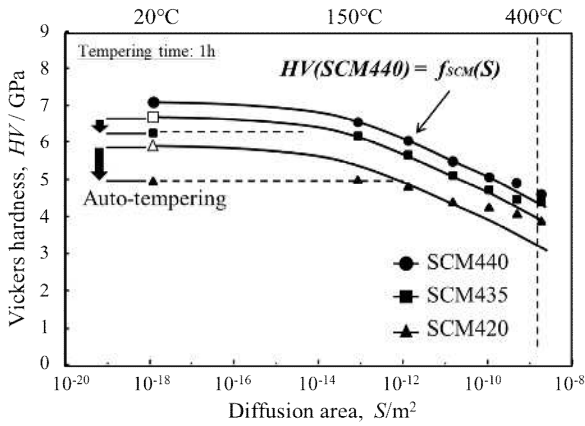
Fig. 1 Relations between diffusion area S and Vickers hardness in specimens with 1h tempering. Open marks show the true hardness of as-quenched martensite without auto-tempering.

decreased uniformly as the tempering temperature increased at temperatures of 200°C and higher. On the other hand, hardness continuously decreased in SCM440 whereas the change in hardness decreased in SCM420 and SCM435 in the temperature range of 200°C and lower. This indicates that auto-tempering occurred during cooling after quenching. We set SCM440 in this state as the standard tempering curve $f_{SCM}(S)$, and estimated the true hardness HV^* for other steels by selecting the A value so that the curve expressed by $HV = A \times f_{SCM}(S)$ matched the experimental values at temperatures of 200 to 400°C and determining the tempering curve for each steel type. We also estimated the true hardness HV^* for carbon steels in a similar fashion by setting S45C as the standard tempering curve $f_{SC}(S)$. Hardness of pure iron martensite can be estimated as 1.75 GPa-HV based on a report by Ueno, et al. and the relationship between the carbon content and Vickers hardness reported by Speich, et al.[4][5] Figure 2 shows the relationship between carbon content and HV^*. Smooth plotting of all data showed that they could be expressed by the following equation:

$$HV^* \text{ [GPa]} = 1.75 + 8.2 \times (\%C)^{1/2} \qquad (2)$$

To standardize the effect of tempering on quenched martensite, we expressed the standardized hardness Hs with the following equation:
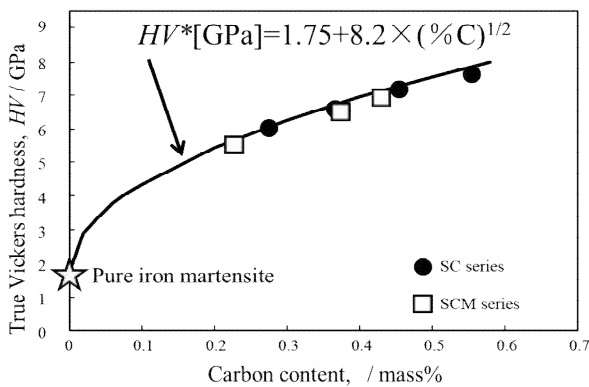
$$Hs = HV / HV^* \qquad (3)$$

Fig. 2 Relations between carbon content (%C) and the true Vickers hardness of as-quenched martensite without auto-tempering; HV^*.

Figure 3 shows the relationship between carbon diffusion area S and Hs with the carbon diffusion activation energy values of carbon steel and chromium-molybdenum steel as 91 kJ/mol and 98 kJ/mol, respectively. Both carbon steel and chromium-molybdenum steel were plotted nearly on the same curve, which can be expressed by the following equation:

$$Hs = 1.0 - 0.0052 \times \{18 + (\log S)\}^2 \qquad (4)$$

As shown above, it is possible to calculate the standardized hardness Hs by determining the carbon diffusion activation energy for each steel type. Therefore, the hardness of tempered martensite can be estimated by using Equations (1), (2) and (3).
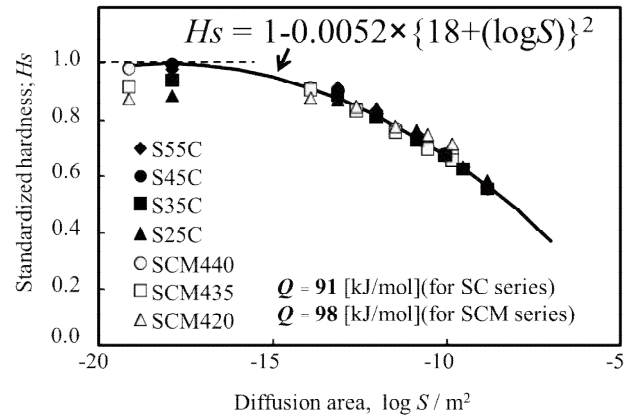

Fig. 3 Relations between diffusion area S and the standardized hardness Hs in specimens with 1h tempering after water-quenching.

3.2 Quantitative evaluation of auto-tempering

Since the temperature continuously changes according to the cooling rate during auto-tempering, which occurs during continuous cooling, auto-tempering needs to be evaluated by using the integrated carbon diffusion area based on the cooling curve. We therefore measured the cooling rate by the distance from the cooling end of the Jominy end-quench test piece. Since the cooling rate decreases with increasing distance from the cooling end, the effect of auto-tempering is also larger. Figure 4 shows
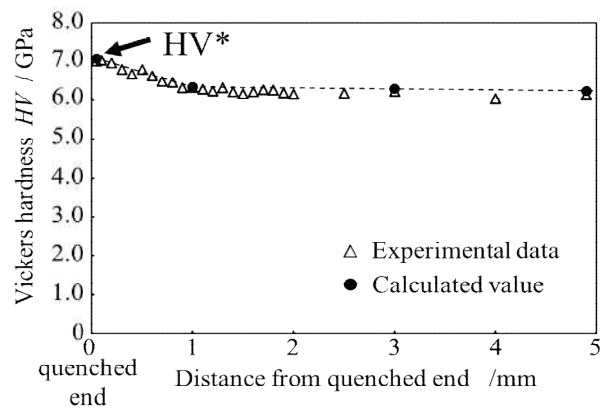

Fig. 4 Jominy curve in SCM440

the distribution of hardness calculated based on the integrated carbon diffusion area, which was calculated from the cooling curve for SCM440, along with the distribution of the hardness of test pieces obtained in experiments. The calculated values closely matched the experiment values. The hardness of the cooling end matched the HV* of SCM440, and considerable auto-tempering was already occurring at 1 mm from the cooling end.

4.Summary

1)The true hardness HV* of quenched martensite without auto-tempering is expressed by HV* [GPa] = 1.75 + 8.2 × (%C)$^{1/2}$ as a function of the carbon content (%C).

2)It is possible to evaluate the temper softening behavior of martensitic steel by using the standardized hardness Hs (= HV / HV*), regardless of the carbon content.

3)The standardized hardness Hs of martensitic steel that underwent auto-tempering can be expressed as a function of diffusion area S (= Dt) by Hs = 1.0 − 0.0052 × {18 + (log S)}^{2}. Here, the value of carbon diffusion activation energy D_0 varies depending on the alloy components.

4)In continuous cooling, the degree of auto-tempering can be quantitatively evaluated with accuracy by calculating the integrated diffusion area S (= Σ Dt) at the M_{50} temperature and lower.

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