Development and Industrial Application of Ultra-Rapid Carburizing Above Eutectic Temperature by Induction Heating

Ryosuke YAMAMOTO[1] and Akio NISHIMOTO[2]

[1] Product Development Department, JTEKT THERMO SYSTEMS CORPORATION, Tenri 632-0084, Japan
[2] Department of Chemistry and Materials Engineering, Faculty of Chemistry, Materials and Bioengineering, Kansai University, Suita 564-8680, Japan

Global attention is focused on carbon neutrality. New carburizing methods are required for the sustainable and environmentally use of heat treatment in the future. Therefore, the authors have so far developed ultra-rapid carburizing. Ultra-rapid carburizing is much faster than conventional carburizing due to the rapid temperature rise by induction heating and carburizing above the eutectic temperature. In other words, this makes it possible to be an efficient process. Previous studies have clarified the carburizing reaction mechanism for ultra-rapid carburizing, and it was verified carburizing reaction is rate-controlled by the decomposition reaction of methane which is the raw material gas. There are some problems to be solve in using this principle in industry. Therefore, we investigated countermeasure against the coarsening of prior austenite grains caused by high temperature treatment, additionally then considered and verified the method of setting the heat treatment conditions. As a result, it was found that prior austenite grain size could be refined to approximately #9 by cooling after ultra-rapid carburizing to form a single layer of martensitic structure and then re-quenching. In addition, we calculated efficient conditions were derived so that the surface carbon concentration was 0.6 mass% and the effective hardened layer depth was 0.8 mm based on the carburizing reaction mechanism and Fick's second law, the amount of carbon diffusion in the steel. Then, we obtained the desired results through experimental verification.

Keywords: *carburizing, high temperature carburizing, induction heating, carbon diffusion, prior austenite grain size*

1. Introduction

A convenient society is due to the benefits of various industrial products. Vehicles and robots are typical examples. A large amount of iron is used in the parts that become those mechanical elements. Because iron is abundant in the earth, and various properties can be imparted to it by making it steel by alloying and by thermochemical treatment. However, heat treatment generally consumes a large amount of energy (electricity, gas e.g.). Currently, the global movement toward a decarbonized society is accelerating. Based on the above background, the heat treatment of industrial products is important for the sustainable realization of a convenient society. Surface hardening treatment for steel is used to impart mechanical properties. Particularly carburizing is effective for fatigue resistance and other properties, and will continue to be an important process in the future. At present, gas carburizing is the main method. However, gas carburizing is beginning to be replaced by low-pressure carburizing due to the effect of reducing carbon dioxide emissions. In general, gas carburizing and low pressure carburizing are lot processes, so there are some problems in the manufacturing process such as inventory management. As shown above, more new carburizing method is required to sustainably use heat treatment. Therefore, authors have developed ultra-rapid carburizing. Ultra-rapid carburizing is much faster than conventional carburizing due to the rapid temperature rise by induction heating and carburizing above the eutectic temperature1). In other words, this makes it possible to be an efficient process. However, ultra-rapid carburizing has the disadvantage of coarsening the prior austenite grains due to the high temperature treatment. Previous studies have clarified the carburizing reaction mechanism for ultra-rapid carburizing, and it was verified carburizing reaction is rate-controlled by the decomposition reaction of methane which is the raw material gas2). But further efforts are required to apply it industrially. Therefore, countermeasures against the coarsening of prior austenite grains due to high-temperature treatment were investigated, and the optimum process was proposed by examining the cooling process after carburizing. And, by calculating the amount of carbon diffusion in steel based on the carburizing reaction mechanism and Fick's second law and examining the process, it became possible to propose appropriate treatment conditions.

2. Experiment

2.1 Sample materials

The material is chrome molybdenum steel (JIS SCM420). Table 1 shows the chemical composition. The sample is turned to a ring-shaped, outer diameter of 139 mm, inner diameter of 89 mm, and width of 25 mm as shown in Figure 1.

Table 1 Chemical composition (mass%)

C	Si	Mn	P	S	Cr	Mo
0.20	0.25	0.78	0.019	0.004	1.10	0.22

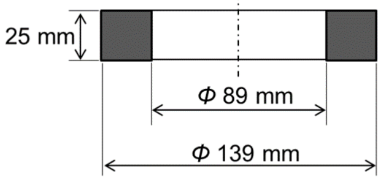

Fig. 1 Shape of sample

2.2 Heat treatment method

Generally in gas carburizing or vacuum carburizing, carburizing process is carried at 1223 K-1325 K. On the other hand, the ultra-rapid carburizing is processed at a temperature above the eutectic temperature (1420 K). Therefore, it is possible to be high-speed carburizing by increasing the carbon diffusion rate. In the experiment, the ultra-rapid carburizing apparatus was made by JTEKT

THERMO SYSTEMS COPORATION. The schematic diagram of apparatus is shown in Figure 2. Consists of two modules can be quenched and carburized using induction heating. A mixed gas of methane and nitrogen is used for carburizing, and water-soluble polymer solution is used for quenching (P.Q.).

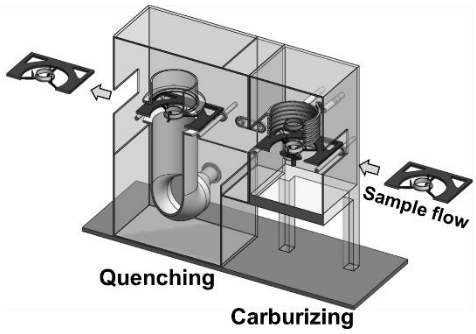

Fig. 2 Structure diagram of apparatus for carburizing and quenching.

2.3 Analysis

Hardness test was evaluated in the cross-sectional using Micro Vickers hardness tester, and the microstructure was observed using an optical microscope.

3. Prior austenite grain coarsening behavior

3.1 Heat treatment conditions

As shown in Figure 3, it is carburized at 1523 K in a methane gas concentration of 10 vol% for 720 s, then cool to 1223 K. At this time, it is austenite single phase. Samples were prepared with three conditions of cooling rate (Slow: 0.25 K/s, Fast: 1.5 K/s, P.Q.:130 K/s*). Here P.Q. indicates polymer quenching; cooling with a water-soluble polymer liquid, and the quenchant temperature is 293 K. The * mark is an estimated value. The re-quenching conditions were two levels of heating temperature, 1123 K and 1223 K, and P.Q. was performed after re-heating for 120 s. Then, the state of the prior austenite grains was evaluated by nital corrosion structure and picric acid-based corrosion of the sample cross section.

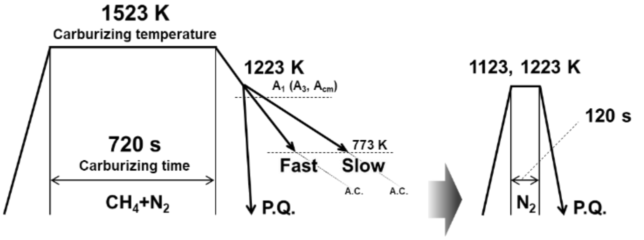

Fig. 3 Heat treatment condition.

3.2 Results and discussion

Figure 4 shows the nital corrosion structure and prior γ grain boundary under P.Q. conditions after carburizing. On the surface, the nital structure is a martensite single phase, and the prior γ grain size is coarsened by high temperature treatment, the grain size number was #2-#3. As a result of re-quenching, the prior γ grain size became finer at all re-quenching temperatures, as shown in Figure 5. In particular, grain size is smaller (approximately #9) at 1123 K, which has a lower re-quenching temperature. Because this is thought to be that grain boundary growth during re-heating was more pronounced at higher re-heating temperature. On the other hand, Figure 6 shows the nital structure and prior γ grain boundary when cooled at 0.25 K/s after carburizing. The nital structure diffusely transforms into a mixed structure of ferrite and bainite due to the slow cooling rate. As a result of re-heating at a relatively low re-heating temperature of 1123 K, the grain size became finer, however became mixed grains. This is due to the fact that the structure before re-quenching is rough and inhomogeneous[3].

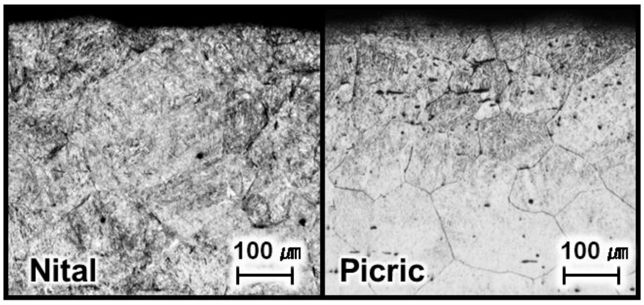

Fig. 4 Surface microstructure and prior γ grain boundaries after carburizing and quenching.

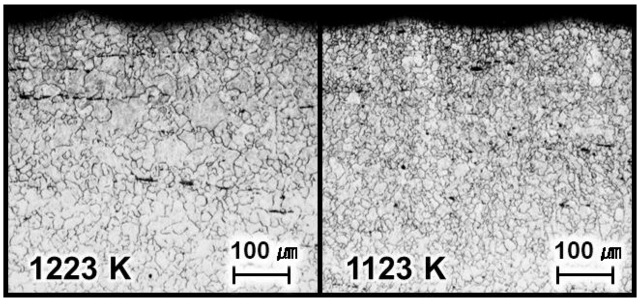

Fig. 5 Surface prior γ grain boundaries re-heated at 1223 K and 1123 K.

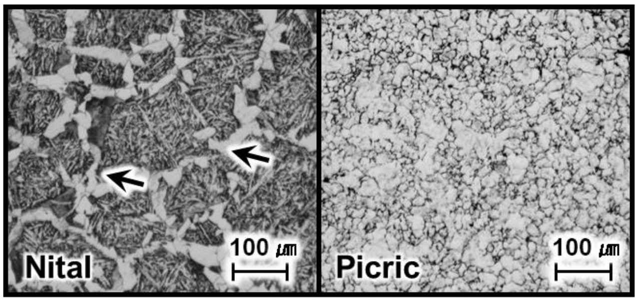

Fig. 6 In-side microstructures for slow cooling.

4. Optimization of treatment conditions

4.1 Calculation model

Commonly to evaluate the effective case depth from the hardness profile is obtained by the hardness test, as for the thermochemical treatment property after carburizing and quenching. Hardness property due to carburizing is affected by the carbon concentration profile in the steel and the quenched microstructure. It is necessary to model the amount of carbon penetrating from the surface and the amount of carbon diffusing in the steel, to predict the carbon concentration profile in steel. In previous research on ultra-rapid carburizing, the rate of penetration of carbon from the steel surface is shown by formula (A)2). Carbon diffusion in steel follows Fick's second law has known, and there are various reports on the carbon diffusion coefficient in steel. In this study, Ågren's formula (B)4) was used, which is expressed as a function of temperature and carbon concentration. Considering these factors, a simple model using the finite difference method was used to predict the carbon concentration in steel. Where $\boldsymbol{F}$ is the carbon flux(m^2·s^{-1}), $\boldsymbol{T}$ is temperature(K), $\boldsymbol{Dc}$ is carbon diffusion coefficient(m^{-2}·s^{-1}), $\boldsymbol{y}_\mathrm{c}$ is carbon concentration in steel(mass%).

$$\boldsymbol{F = 4.04 * 10^{-11} e^{(1.20*10^{-2}T)}} \cdots \text{(A)}^{2)}$$

$$\boldsymbol{D_\mathrm{c}(T, C) = 4.53 * 10^{-7}\{1 + y_c(1 + y_c)8339.9 * T\} e^{\{-(1/T - 2.221*10^{-4})(17767 - y_c*26436)\}}} \cdots \text{(B)}^{4)}$$

4.2 Examination of carburizing conditions

Conditions were examined using a prediction model and verified by carburizing and quenching. The target heat treatment properties were calculated so that the surface carbon concentration was 0.6 mass% and 0.8 mass%, and the effective case depth was 0.8 mm at 0.3 mass%. The sample shown in Figure 1 was quenched (P.Q.) in advance, and it was confirmed that the surface carbon concentration was 0.3 mass% when the hardness was 550HV. The carburizing temperature, carburizing time, and diffusion time were repeatedly calculated to achieve the desired properties at each methane gas concentration. Table 2 shows the conditions with the shortest processing time among the calculation results. Figure 7 shows the predicted carbon concentration profile.

Table 2 Shortest process conditions.

	Carburizing temperature, K	Processing time, s	CH_4, vol%
(a)	1573	502	9
(b)	1563	438	11

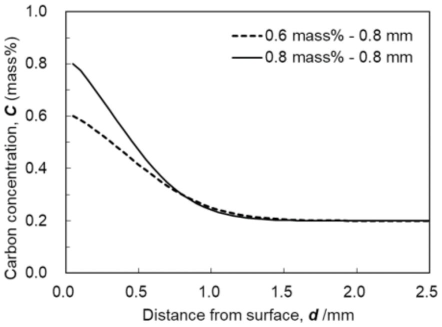

Fig. 7 Predicted carbon concentration profiles.

4.3 Experimental verification results and discussions.

Figure 8 shows the hardness test results. The effective case depth was 0.87 mm in condition (a) and 0.79 mm in condition (b) against the target of 0.8 mm, thus these are almost the same with the predicted result. Figure 9 shows the nital structure near the surface of the cross section of the sample. Retained austenite was observed near the surface under condition (b) compared to condition (a). It shows that the surface hardness decreased under the condition (b) shown in Figure 9 due to the effect of retained austenite. It was also confirmed that the surface carbon concentration was higher in condition (b) because the quenching conditions were the same.

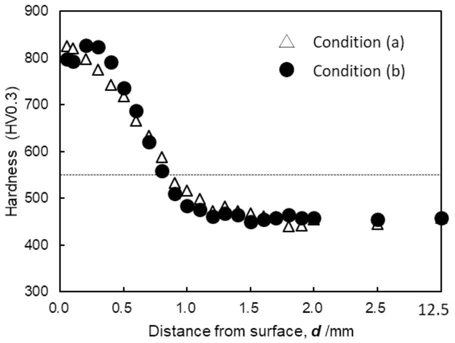

Fig. 8 Hardness profiles for optimal conditions (a) and (b).

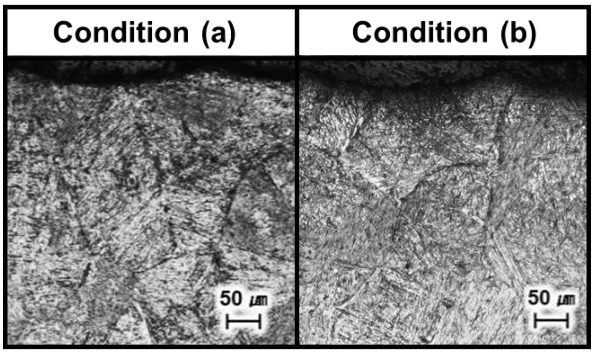

Fig. 9 Surface microstructures for optimal conditions (a) and (b).

5. Conclusion

In summary, the following results were obtained as a result of investigating methods for addressing coarsened of prior austenite grains and optimal conditions for the industrial use of ultra-rapid carburizing.

(1) The grain size number of prior austenite grains is coarsened to #2 or #3 by ultra-rapid carburizing and quenching.
(2) The grains become finer after re-quenching, when the martensite is single-phased after ultra-rapid carburizing and quenching.
(3) The results of optimizing carburizing condition showed good agreement with the actual measurement, using the model that predicts the distribution of carbon concentration due to carburizing at the cross section of the sample.
(4) The processing time can be reduced and the amount of raw material gas used can also be reduced by optimizing carburizing condition.
(5)These results are indicative of being close to industrial and carbon-neutral methods.

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