Influence of Induction Heating Conditions on Quenched Structure of SUJ2 Steel

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When JIS-SUJ2 steel is hardened by induction heating, high-temperature austenitization is applied in order to achieve high throughput. In this case, SUJ2 is quenched from the single-phase austenite zone. As a result, the properties of SUJ2 may be different from those obtained by a conventional furnace process involving SUJ2 quenched from the two-phase austenite/cementite zone. In this study, we experimentally investigated the relationship among the amount of undissolved carbide, austenitization temperature, and holding time. Additionally, we developed a formula for predicting the amount of undissolved carbide. The formula is constructed from the Arrhenius equation and the Kolmogorov-Johnson-Mehl-Avrami equation. Subsequently, the effect of the austenitization temperature and the amount of undissolved carbide on the hardness, retained austenite content, prior-austenite grain size, and martensite block size were investigated.

KEY WORDS: heat treatment; bearing steel; induction heating; grain size; retained austenite.

1. Introduction

JIS-SUJ2 is the most common steel used for rolling bearings. In the heat treatment of SUJ2 steel, the steel is normally retained for a certain period of time under a high-temperature endothermic converted gas atmosphere and followed by quenching. Carbide dissolves into austenite during the high-temperature retention, and the austenite with dissolved carbon is quenched. The dislocation density increases owing to martensitic transformation, and high hardness is obtained as a result. In general, endothermic converted gas is usually used for the carburization treatment of low-carbon steel, while in the case of SUJ2 steel, a sufficient amount of carbon is intrinsically contained in the steel, thus, it is not necessary to supply carbon from the outside, and endothermic converted gas is used to suppress the decarburization and oxidation of the surface.

In order to reduce cost and to realize simple operation, the heating of SUJ2 steel may be carried out in an inert gas atmosphere instead of an endothermic converted gas atmosphere. It has been found that almost the same heat-treatment quality can be obtained as that obtained in an endothermic converted gas atmosphere. However, furnace heating and cooling takes a long time; therefore, day-and-night continuous operation is necessary.

In order to solve this problem, the application of induction heating is promising. In induction heating, eddy currents are induced directly into the target and generate heat. Therefore, it is not necessary to use a furnace, and heating can be easily initiated and terminated. Since heating is carried out in air, the surface of the target may be oxidized, but the heating time is short, so the affected area will be limited to only the surface layer.

On the other hand, one of the drawbacks of induction heating is low throughput. In order to compensate for this drawback, high-temperature heating is usually adopted. Higher temperature accelerates the dissolution of carbide into austenite; thus, the heating time can be shortened. However, when the austenitization temperature is 900°C or higher, SUJ2 steel is retained in the austenite single-phase zone of equilibrium diagram, and the properties may be different from those obtained by furnace heating, in which SUJ2 steel is retained in the austenite/cementite two-phase zone.

In the past, the relationships among various properties and the amount of undissolved carbide were investigated after quenching SUJ2 steel. However, the austenitization was carried out by furnace heating around less than 900°C; thus, the properties with high-temperature short-time heating, such as by induction heating, were not evaluated. In addition, the austenitization temperature had been changed to vary the amount of undissolved carbide; thus, there has been no systematic investigation of the various properties when the amount of undissolved carbide and austenitization temperature are independently adjusted.

The dissolution process of carbide has been investigated by X-ray diffraction and with a dilatometer, but there has been no report that focused on the amount of undissolved carbide after heat treatment.
In this study, the relationship among the austenitization temperature, holding time, and amount of undissolved carbide was experimentally clarified. The effect of the austenitization temperature and the amount of undissolved carbide on the amount of retained austenite, hardness, prior-austenite grain size, and martensite block size was investigated after heat treatment. In addition, the amount of surface decarburization by heating in air was also investigated.

2. Experimental Procedures

2.1. Method for Test Piece Preparation by Varying the Austenitization Temperature and Amount of Undissolved Carbide

Table 1 shows the chemical composition of SUJ2 steel used in the tests. In all the tests, steels subjected to spheroidized annealing were used.

Figure 1 is a photograph of the test piece. Ring-shaped test pieces with an outer diameter of 60.3 mm, an inner diameter of 53.7 mm, and a width of 15.3 mm were used. An induction coil with an outer diameter of 103 mm, an inner diameter of 74 mm, and a width of 22 mm was used for induction heating. The power supply was a series-resonant type, and the current frequency was 80 kHz. The coil current was held constant at 1 300 Arms until the temperature of the test piece reached the austenitization temperature, then feedback-controlled to maintain the temperature. The temperature of the test piece was measured using a thermocouple welded at the central section along the width direction on the outside surface. Figure 2 illustrates the temperature variation when the austenitization temperature was 900°C, and the duration was 57 s. After austenitization at each austenitization temperature for a specified time, the test piece was cooled in quenching oil (cold oil, severity of quench factor H is about 0.14 cm⁻¹) at 70°C until the surface temperature reached 100°C.

Tempering was performed at 180°C × 2 h or 240°C × 43 s; in the former case, heating was by furnace heating, while in the latter case, by induction heating. The hardness after tempering was similar to each other for both conditions.

The samples with austenitization temperatures of 900, 950, and 1 000°C, and with the amount of undissolved carbide in the range of 3.5–12.1% were tested. The amount of undissolved carbide was adjusted by varying the holding time. The duration was adjusted in the ranges of 11–316 s, 3–65 s, and 0.7–10.3 s when the austenitization temperature was 900°C, 950°C, and 1 000°C, respectively.

2.2. Method for Observation of Structure

Microstructure in the vicinity of the thermocouple-welded site was observed. Figure 3 shows a schematic illustration of the observed cross-section. After etching with an ethanol solution of picric acid, the observation was carried out with a scanning electron microscope (SEM). The area fraction of undissolved carbide was measured by image analysis. Since the distribution of carbide is not uniform due to the influence of segregation, 15 images were continuously acquired in the direction perpendicular to the segregation and the mean value was determined. In this study, the amount of undissolved carbide was defined as the area fraction of undissolved carbide.

Prior-austenite grains were observed with an optical microscope after etching with a revealing solution in which
picric acid is the main component. The grain size analysis was carried out by the sectioning method of ASTM.\(^\text{10}\) The martensite block size was observed by field emission scanning electron microscopy/electron backscatter diffraction method (FE-SEM/EBSD).

2.3. Measurement of Retained Austenite
The surface region up to 0.1 mm thick below the top-surface was removed by electropolishing, and the amount of retained austenite was determined by X-ray diffraction, in which the intensity of \(\alpha (211)\) and \(\gamma (220)\) were compared. The measurement position was in the vicinity of the thermocouple-welded site.

2.4. Measurement of the Amount of Decarburization
On the cross-section surface shown in Fig. 3, electron probe microanalysis (EPMA) was carried out from the surface of the outer diameter to a depth of 0.5 mm (spot diameter: 2 \(\mu\)m, measurement interval: 2 \(\mu\)m). The carbon concentration was calculated using a calibration curve prepared from samples whose carbon concentrations were already known.

3. Results

3.1. Relationship Among Austenitization Temperature, Holding Time, and Amount of Undissolved Carbide
Figure 4 illustrates the distribution of carbide when the austenitization temperature was 900°C and the holding time was 70 s. The relationship between amount of undissolved carbide and holding time is shown in Fig. 5 for various austenitization temperatures.

As in the past report,\(^\text{11}\) a prediction formula was constructed from the Kolmogorov-Johnson-Mehl-Avrami equation\(^\text{12}\) (Eq. (2)) and Arrhenius equation (Eq. (3))

\[
f = 1 - \exp(-Kt^n) \quad (2)
\]

\[
K = A \exp\left(\frac{-Q}{RT}\right) \quad (3)
\]

where \(f\) is the dissolution rate of carbide, \(K\) is the rate constant, \(t\) is holding time (s), \(T\) is absolute temperature, \(R\) is the gas constant, and \(n, A, Q\) are constants.

Samples subjected to spheroidized annealing consists of ferrite and spheroidal cementite. If we assume that all of the carbon is present in cementite, the initial amount of carbide can be calculated to be 15.6%. It is assumed that the density of ferrite was 7 860 kg/m\(^3\), and the density of cementite was 7 680 kg/m\(^3\).\(^\text{13}\) The amount of undissolved carbide after austenitizing for an infinite amount of time was assumed to be 0%. Thus, the unknowns, \(n, A, Q\) in Eqs. (2) and (3) were determined by the least-squares method using experimental results in Fig. 5. As a result, the prediction formula (Eq. (4)) for the amount of undissolved carbide \(M (\%)\) at austenitization temperature \(T (°C)\) and time \(t (s)\) could be constructed, as follows.

\[
M = 15.6 \exp\left(-1.71 \times 10^7 \exp\left(-\frac{1.88 \times 10^5}{RT}\right) t^{0.531}\right) \quad (4)
\]

Figure 6 shows the relationship between the experimental values of the amount of undissolved carbide and the predicted values with Eq. (4). The coefficient of determination (contribution rate \(R^2\)) was 0.968; therefore, the amount of...
undissolved carbide can be precisely predicted by Eq. (4) at least within the range of the austenitization temperature of 900–1 000°C.

### 3.2. Effects of Austenitization Temperature and the Amount of Undissolved Carbide on the Material Structure

For samples with austenitization temperatures of 900, 950, and 1 000°C, and the amount of undissolved carbide of about 4, 8, and 12%, the amounts of retained austenite, hardness, and prior-austenite grain size were measured. In addition, as for the samples with austenitization temperatures of 900 and 950°C, and the amount of undissolved carbide of about 4, 8, and 12%, the martensite block size was also measured.

**Figure 7** shows the measurement results for the amount of retained austenite. The amount of retained austenite increased with increasing austenitization temperature and with decreasing undissolved carbide. In the cases of the same amount of undissolved carbide, a higher austenitization temperature leads to larger amount of retained austenite.

**Figure 8** shows the measurement results of hardness. When the austenitization temperature was 900°C, the hardness increased with decreasing undissolved carbide. When the austenitization temperature was 950°C, the hardness was higher when the amount of undissolved carbide was 8% than when it was 12%; however, it was reversed when the amount of undissolved carbide was 4%. This is considered to be due to the increase in the percentage of the retained austenite. When the austenitization temperature was 1 000°C, the hardness was high even in the case that the amount of undissolved carbide was large, namely, in the case that the amount of dissolved carbon was small.

**Figure 9** illustrates prior-austenite grain structures when the austenitization temperature was 900°C. The measurement results of the prior-austenite grain size are shown in **Fig. 10**. The larger the amount of undissolved carbide, the larger the grain size number. However, even when the amount of undissolved carbide was 4%, the grain size number increased with increasing austenitization temperature.
ber was about 9; thus, grain coarsening could be suppressed by the pinning effect of carbide, as small as 4%. Although the grain size became larger with increasing austenitization temperature, the difference was very small. Within the present experimental range, the effect of the austenitization temperature on the grain size was found to be small.

Figure 11 illustrates the crystallographic orientation of martensite when the austenitization temperature was 900°C. Areas with an orientation difference with an orientation difference of less than 5° were regarded as one block; thus, the equivalent diameter was calculated and this was considered to be the martensite block size. The maximum, the minimum, and the mean value of the martensite block size at the respective evaluation levels are shown in Table 2. Figure 12 shows the relationship between the mean value of martensite block size and the amount of undissolved carbide. The mean value tended to be smaller when the amount of undissolved carbide was 8% than when it was 4% and 12%.

### 3.3. Amount of Decarburization

Figure 13 shows the carbon profiles of samples austenitized at 900°C measured by EPMA. The spot diameter was 2 μm; thus, it was difficult to distinguish various components, such as the tempered martensite, retained austenite, undissolved carbide, and ε carbide. When the surface carbon concentration was lower than the mean interior carbon concentration, this was defined as decarburization and the depth of the decarburization was investigated. The results are shown in Fig. 14. At any austenitization temperature, decarburization did not take place when the amount of undissolved carbide was 12%. When the amount of undis-
solved carbide became smaller, such as 4% or 8%, slight decarburization took place. The maximum decarburization depth was about 0.02 mm when the amount of undissolved carbide was 8% and about 0.08 mm when it was 4%.

4. Discussion

Here, the prediction formula for the amount of undisolved carbide in SUJ2 steel is discussed. In Section 3.1, the constant $n$ was assumed to be independent of temperature to predict the amount of undissolved carbide at any austenitization temperature. Here, the constants $n$ and $K$ are recalculated for each austenitization temperature. The following equation is obtained by double logarithm of Eq. (2).

$$\ln \ln \left( \frac{1}{1-f} \right) = n \ln t + \ln K$$

For each austenitization temperature, $\ln \ln(1/(1-f))$ was plotted versus $\ln t$ for each condition shown in Fig. 5. From the slope and the intercept of the obtained approximating straight line (Fig. 15), $n$ and $K$ were determined. The results are summarized in Table 3.

For 950°C and 1 000°C, $n$ was almost the same; however, $n$ for 900°C was about 20% smaller than it was for 950°C and 1 000°C. This indicates that the carbide dissolution mechanism at 900°C is different from that at 950 and 1 000°C. On the equilibrium phase diagram of SUJ2, the point of 900°C and 1.02 mass% C is located at the lower temperature side than the Acm line. Thus, carbide is not dissolved completely in the equilibrium state, which could be the cause of the difference in $n$. Therefore, the equilibrium phase diagram for the components of the test piece was estimated using the thermodynamic equilibrium calculation software FactSage, and the amount of cementite in equilibrium at 900°C was calculated. The equilibrium phase diagram is shown in Fig. 16. In the calculation results, the volume fraction of cementite in equilibrium was about 0.2%. By using this value, $n$ was recalculated to be 0.4860 for the austenitization temperature of 900°C. The difference became smaller; however, the value was still smaller than $n$ in the case of 950 or 1 000°C.

The constant $n$ signifies the ease of reaction; therefore, it is considered that some difficulty in carbide dissolution process is present in the case of 900°C compared with the cases of 950 and 1 000°C. The carbide dissolution process is broadly divided into two steps. The first step is the process in which the diffusion of carbon limits the rate of carbide dissolution, and the second step is the process in which the diffusion of alloying elements limits the rate. In the first step, austenite transformation also progresses at the same time. When the austenitization temperature is 910°C or higher, all of the ferrite transforms instantly; however, when it is less than 910°C, carbon necessary for austenitization needs to be supplied from carbide. Accordingly, the austenitization takes a longer time when the austenitization temperature is 900°C or higher, all of the ferrite transforms instantly; however, when it is less than 910°C, carbon necessary for austenitization needs to be supplied from carbide. Accordingly, the austenitization takes a longer time when the austenitization temperature is 900°C compared with 950 or 1 000°C. However, the difference between 900°C and 910°C is small; therefore, the amount of carbon necessary for transformation seems to be small, and the austenitization may complete within a short time. Therefore, this is hardly considered to be the cause of the difference in $n$.

The diffusion rate of alloying elements, which limits the rate of the second step, is very slow compared with the

| Temperature (°C) | $n$   | $K$    |
|------------------|-------|--------|
| 900              | 0.4754| $9.52\times10^{-2}$ |
| 950              | 0.5733| $1.41\times10^{-1}$ |
| 1 000            | 0.5689| $3.22\times10^{-1}$ |

Fig. 14. Influence of austenitization temperature and undissolved carbide fraction on maximum decarburization depth.

Fig. 15. Plots of $\ln \ln(1/(1-f))$ vs $\ln t$ for different austenitization temperature. (a) 900°C, (b) 950°C, and (c) 1 000°C.

Table 3. Values of $n$ and $K$ in formula (2) for different austenitization temperatures determined from the plots shown in Fig. 15.
diffusion rate of carbon that limits the rate of the first step. Therefore, the rate of the dissolution process of carbide is largely limited by the diffusion of alloying elements. Accordingly, the difference in $n$ is considered to be due to the difference in the diffusion rates of the alloying elements. When the austenitization temperature is 950 or 1000°C, carbide is completely dissolved in the equilibrium state; however, carbide is undissolved in the case of 900°C as shown in Fig. 16, thus, it is difficult for alloying elements to diffuse out of existing carbides. As a result, the diffusion of alloying elements is considered to be difficult in the case of 900°C.

When we expand Eq. (4) to lower than 900°C, we need to further investigate the carbide dissolution process by considering the amount and also the stability of carbide in the equilibrium state.

5. Conclusions

In this study, the relationship among the austenitization temperature, duration, and amount of undissolved carbide during heating of JIS-SUJ2 steel was clarified. A prediction formula for the amount of undissolved carbide was constructed, and the hardness after quenching, the amount of retained austenite, prior-austenite grain size, martensite block size, and the decarburization depth of the surface were investigated. The verification ranges were 900–1000°C for the heating temperature and 3.5–12.1% for the amount of undissolved carbide. The results are summarized below.

(1) A prediction formula for the amount of undissolved carbide in SUJ2 steel for the austenitization temperature range of 900–1000°C was constructed. The amount of undissolved carbide $M$ (%) can be predicted from the austenitization temperature $T$ (K) and the duration $t$ (s) using the equation below.

$$M = 15.6 \exp \left( -1.71 \times 10^7 \exp \left( -\frac{1.88 \times 10^7}{RT} \right) \right)^{0.531}$$

(2) The higher the austenitization temperature and the smaller the amount of undissolved carbide, the larger the amount of retained austenite. The hardness after quenching increased with a decrease in the amount of undissolved carbide when the austenitization temperature was 900°C. Similar results were observed when the austenitization temperature was 950°C; however, it was reversed when the amount of undissolved carbide was reduced to 4%, which may be due to the presence of retained austenite. The prior-austenite grain size tended to become larger with a decrease in the amount of undissolved carbide, and the effect of the austenitization temperature was small.

(3) The mean value of the martensite block size after quenching tended to be smaller when the amount of undissolved carbide was 8% than when it was 4% or 12%, and it was about 0.35 μm.

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