Original Article

Study of bainitic transformation kinetics in SAE 52100 steel

Yuming Pan a, Bingxu Wang b,*, Gary C. Barber a

a Automotive Tribology Center, Department of Mechanical Engineering, School of Engineering and Computer Science, Oakland University, Rochester, Michigan, 48309, USA
b Faculty of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, Hangzhou, Zhejiang, 310018, PR China

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Abstract

The objective of this research was to investigate the bainitic formation in austempered SAE 52100 steel. The original microstructure of SAE 52100 steel consisted of spheroidized pearlite. In the formation of bainite, SAE 52100 steel samples were austenitized at a temperature of 849 °C for 20 min, and then quickly quenched to the isothermal temperatures between 232 °C and 427 °C for various holding times from 20 s to 120 min. The hardness and microstructure of austempered SAE 52100 samples were analyzed using a Rockwell C hardness tester and metallurgical optical microscope. In addition, the bainitic formation in SAE 52100 steel was characterized using the theory of kinetic phase transformation. The activation energies of lower bainite and upper bainite microstructure were found to be 4.72 × 10⁴ J/mol and 6.07 × 10⁴ J/mol with frequency factors of 23.03 (1/s) and 273.85 (1/s), respectively.

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1. Introduction

SAE 52100 is an alloy steel with high carbon with chromium as an alloying element, which has been widely applied in rolling bearings [1]. The traditional heat treatment process for SAE 52100 steel consists of a quenching process followed by a tempering step at low temperature. The resulting tempered martensite microstructure provides SAE 52100 steel with high strength and high fatigue resistance [2].

An isothermal heat treatment process has been suggested as an alternative process to produce bainite microstructure in order to provide excellent mechanical properties including high toughness, strength and wear resistance [3,4]. The bainite microstructure can be classified into upper and lower bainite in terms of the carbide precipitation. In upper bainite, most of the carbide is present within the interface between ferritic sheaves. In lower bainite, most of the carbide is formed inside the ferritic platelets without any carbon transfer [5-7].

Krishna et al. [8] investigated the impact toughness and wear resistance of austempered SAE 52100 steel produced at an austempering temperature of 340 °C with holding durations of 10 min, 20 min and 30 min. They found that the impact toughness of austempered SAE 52100 steel specimens increased when they extended the holding duration due to the presence of more bainitic structure in the matrix. In their abrasion wear test, the wear loss of austempered specimens was much lower than that of annealed specimens. Kar et al. [9] applied a two-cycle austenitizing process (1st austenitizing step: 1150 °C, 60 min; 2nd austenitizing step: 900 °C, 20 min)
followed by an isothermal thermal heat treatment step at 255 °C with a holding time of 60 min on SAE 52100 steel. Finally, they reported that using the two-cycle austenizing process could result in doubling of the fracture toughness as compared with conventional quenched and tempered heat treatment. Kilicli et al. [10] demonstrated that varying austempering temperature was more effective than varying holding time in isothermal heat treatment on the fraction of bainite produced in SAE 52100 steel. Bainite + martensite microstructure was found to yield high levels of hardness (55–64 HRC) and enhanced impact toughness (24–54 Joule). Sari et al. [11] found that nitrogen and carbon dioxide ion implantation could be used to modify the mechanical properties of a wide range of metals and alloys using plasma techniques for ion sources and plasma surface treatment. The hardness of SAE 52100 samples could be increased 30–49% using N + 2 ions, and 5–17% using CO2+ ions. Chakraborty et al. [12] found that an optimum austempering process (270 °C, 30 min) followed by water quenching can develop a bainite + martensite duplex microstructure and improved levels of hardness (62HRC) and tensile (2250 MPa) and impact strength (53J).

In the past two decades, researchers have investigated the mechanical properties of austempered SAE 52100 steel. However, few researchers thoroughly studied the formation and morphological transformation of bainitic structure in the matrix of SAE 52100. In this study, eight austempering temperatures and twenty-three holding times were utilized for detailed analysis. The Rockwell hardness and microstructure were studied using a hardness tester and optical microscopy. Also, the transformation kinetics of bainitic formation are characterized in this research.

2. Experimental procedure

2.1. Chemical composition

The chemical composition of the SAE 52100 steel used in this research is shown in Table 1.

2.2. Heat treatment process

2.2.1. As-received SAE 52100 steel
The microstructure of as-received SAE 52100 steel is shown in Fig. 1. It can be seen that the spheroidized carbide is uniformly distributed in the ferrite substrate.

2.2.2. Isothermal heat treatment process
The fully spheroidized SAE 52100 steel cylindrical specimens with a diameter of 15 mm and thickness of 10 mm were first austenitized at 850 °C (1560 °F) for 20 min in a salt bath furnace. Then the fully austenitized specimens were rapidly transferred to another salt bath furnace for the austempering step. Eight different austempering temperatures of 232 °C (450 °F), 260 °C (500 °F), 288 °C (550 °F), 316 °C (600 °F), 343 °C (650 °F), 371 °C (700 °F), 399 °C (750 °F) and 427 °C (800 °F) and twenty-three holding times of 20 s, 40 s, 60 s, 80 s, 100 s, 120 s, 150 s, 180 s, 210 s, 240 s, 270 s, 300 s, 360 s, 420 s, 480 s, 540 s, 570 s, 600 s, 1200 s, 1800 s, 3600 s, 5400 s and 7200 s were used, respectively. The austempered specimens were cooled to room temperature by water quenching. The sketch of the heat treatment process is shown in Fig. 2. The molten salt bath furnaces were used in this research in order to eliminate or minimize the effects of any oxidation and decarburization.

2.3. Rockwell hardness measurement
The hardness of the austempered SAE 52100 steel specimens were measured using a Rockwell C hardness tester. The specimens were ground and polished to produce smooth and flat surfaces for accurate measurements. The hardness measurement on each specimen was repeated three times and averages were reported.
2.4. Metallurgical evaluation

The cylindrical specimens were hot mounted using polymer resin powder. The surfaces of the mounted specimens were ground using SiC sandpaper ranging from 240-grit to 1200-grit and polished using 0.05 μm Al₂O₃ suspension to a mirror-like finish. Then, the mounted specimens were etched using 3% nital solution for approximately 2 s to 3 s. Finally, optical microscopy was used to observe the microstructure of the SAE 52100 specimens.

3. Results and discussion

3.1. Rockwell C hardness measurement

The hardness measurements of austempered SAE 52100 steel specimens produced by various austempering temperatures and holding times are plotted in Fig. 3. For all austempering temperatures, it was found that the hardness drops over a certain period and then gradually becomes flat. The holding times when the hardness starts to drop and then remains flat are defined as the beginning and ending points of the bainitic transformation reaction from austenite. The beginning point of bainitic transformation begins earlier with increasing austempering temperature. In addition, the slope of the transition period became larger at higher austempering temperature. This is because the rate of carbon diffusion is accelerated at high austempering temperature. The rate of the transformation reaction was also accelerated by faster diffusion of carbon at high temperature.

3.2. Morphological analysis of bainite

The microstructures of austempered SAE 52100 steel specimens produced by various austempering temperatures and holding times are shown in Fig. 4. The main components in the matrix are bainite (black regions), martensite (dark brown regions) and retained austenite (light-colored regions). The amount of bainite increases significantly when using longer holding times. Eventually, the matrix becomes 100% bainite. The bainite platelets become coarse at higher austempering temperatures. The bainite produced when using lower austempering temperatures between 232 °C and 316 °C consists of narrow needle-like ferrite sheaves. However, the bainite formed at higher austempering temperatures of 372 °C and 427 °C are considered as upper bainite due to formation of bainitic islands in the matrix. Both upper and lower bainite are
Fig. 4 – Microstructures of Austempered SAE 52100 Steel with Different Austempering Temperatures and Holding Times (a) 232 °C (450 °F) (b) 260 °C (500 °F) (c) 288 °C (550 °F) (d) 316 °C (600 °F) (e) 343 °C (650 °F) (f) 372 °C (700 °F) (g) 399 °C (750 °F) (h) 427 °C (800 °F).
found in the microstructure of the SAE 52100 steel produced by an austempering temperature of 343 °C.

3.3. Transformation kinetics study

3.3.1. Phase transformation fraction

The fraction of bainitic transformation was determined by using hardness measurements, see Eq. 1. In Fig. 5, it can be seen that the transformation rate increases when increasing the austempering temperatures.

\[ X_t = \frac{H_0 - H_f}{H_0 - H_b} \times 100\% \quad (1) \]

Where:
- \( X_t \) – The fraction of bainitic transformation
- \( H_0 \) – The initial hardness, which corresponds to the beginning of the bainitic transformation reaction
- \( H_b \) – The hardness measured at a specific holding time during the bainitic phase transformation
- \( H_f \) – The final hardness, which corresponds to the end of the bainitic transformation reaction

The “Avrami” equation (Eq. 2) can be used to describe the relationship between the phase transformation and specific holding durations. For each austempering temperature.

\[ X_t = 1 - \exp(-kt^n) \quad (2) \]

Where:
- \( X_t \) – Transformation fraction after a specific holding time
- \( k \) – Rate coefficient of the transformation reaction
- \( n \) – Slope of “Avrami” plot

The above Eq. 2 can be reorganized as follows (Eqs 3 and 4) to determine the values of “k” and “n”.

\[ \ln[-\ln(1-X)] = \ln k + n\ln t \quad (3) \]

\[ n = \frac{\Delta \ln [-\ln(1-X)] - \ln k}{\Delta \ln t} \quad (4) \]

The values of “k” and “n” were obtained from the plots of the organized “Avrami” equation. “k” was the y intercept of the best fit line, and “n” was the slope of the regression equation. The regression equations for each austempering temperature are shown in Fig. 6.

The linear regression equations for each austempering temperature are shown in Table 2. The values of “k” and “n” are summarized in Table 3.
### 3.3.2. Activation energy

The activation energy is the minimum energy required to initiate a chemical reaction. According to the "Arrhenius" equation (Eq. 5), the activation energy for both upper and lower bainite was found as follows:

\[ k e^{-Q/RT} = A \times \]  

(Eq. 5)

Where:
- \( k \) – Rate coefficient of the transformation reaction [1/s]
- \( A \) – Reaction frequency factor [1/s]
- \( R \) – General gas constant [J/mol × K]
- \( Q \) – Activation energy [J/mol]
- \( T \) – Temperature [K]

The above "Arrhenius" equation can be rewritten as shown in equation 6 to determine the values of "Q" and "A". The plots of "lnk" versus “1/T” are shown in Fig. 7.

\[ \ln k = -\frac{Q}{RT} + \ln A \]  

(Eq. 6)

The values of "Q" and "A" can be determined by the slope of the regression line and intercept with Y axis, see Table 4.

### Table 4 – The Values of "Q" and "A" for Upper and Lower Bainitic Transformation.

<table>
<thead>
<tr>
<th>Bainite</th>
<th>Q (J/mol)</th>
<th>A (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>4.72 × 10^{-4}</td>
<td>23.03</td>
</tr>
<tr>
<td>Upper</td>
<td>6.07 × 10^{-4}</td>
<td>273.65</td>
</tr>
</tbody>
</table>

### 4. Summary and conclusions

In this research, austempered SAE 52100 steel specimens were produced using various austempering temperatures and holding times. The Rockwell C hardness and microstructure of bainitic SAE 52100 steel were evaluated. Also, the transformation kinetics of bainitic formation was studied. Several conclusions can be summarized as follows:

1. Lower bainite was produced using austempering temperatures ranging from 232 °C (450 °F) to 343 °C (600 °F). The ferrite platelets became coarse and upper bainite was produced when using the austempering temperatures of 372 °C (700 °F) and 427 °C (800 °F).
Fig. 6 – Plot of “ln[-ln(1-X)]” versus “ln t” for Various Austempering Temperatures (a) 232 °C (450 °F) (b) 260 °C (500 °F) (c) 288 °C (550 °F) (d) 316 °C (600 °F) (e) 343 °C (650 °F) (f) 372 °C (700 °F) (g) 399 °C (750 °F) (h) 427 °C (800 °F).

Fig. 7 – Linear Relationship between “lnk” versus “1/T” (a) Lower Bainite (232 °C (450 °F) - 343 °C (650 °F)) (b) Upper Bainite (343 °C (650 °F) - 427 °C (800 °F)).
2 The austempering temperature of 343 °C (650 °F) seemed to be the threshold since both lower and upper bainite could be found in the matrix produced at 343 °C (650 °F).
3 Hardness decreased when increasing either isothermal temperature or holding time.
4 The beginning of the bainitic transformation occurred earlier when increasing the austempering temperature.
5 The transformation rate of upper bainite was higher than that in lower bainite.
6 The activation energy required for the formation of upper bainite was higher than that for lower bainite.

**Conflict of interest**

All authors declared no conflict of interest.

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