

Effect of Austenite Grain Size on the Fatigue Strength of Vacuum Carburized Low Carbon Steel Sheets after Quenching

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Abstract:

In recent years, since the application of the vacuum carburizing and quenching process has expanded, prompting an exploration of guidelines for improving fatigue strength. In this study, vacuum carburizing and quenching were performed on low carbon steel, and the plane bending fatigue strength was evaluated. Specimens were prepared under different quenching temperature conditions after vacuum carburizing, and fatigue tests were conducted. The results indicated that fatigue strength tends to increase as the prior γ grain size becomes finer; however, when the maximum grain size of the prior γ was below 47 μm , the increase in fatigue strength was minimal. Observations of fracture surfaces suggested that the transition of the fatigue failure initiation point from intergranular fracture to transgranular fracture was a contributing factor. It was suggested that in vacuum carburized and quenched materials, achieving a sufficiently fine prior γ grain size can lead to a stable and high fatigue strength, as the initiation point of fatigue failure shifts to intragranular fracture.

1. Introduction

In recent years, due to strong demands for reducing carbon dioxide emissions, there has been a significant push to improve fuel efficiency in automobiles by making automotive components lighter and more compact. Transmission components, such as torque converters, require high fatigue strength to withstand repeated loads from shifting operations and engine vibrations. To enhance the fatigue strength of these components, surface hardening treatments such as carburizing and quenching are applied. Improving the fatigue strength of carburized and quenched components has become

an important challenge.

Gas carburizing is widely used in industrial applications for carburizing processes. Numerous studies have been conducted on the fatigue strength of gas carburized materials, reporting various influencing factors such as surface hardness^{1, 2)}, grain boundary oxidation layers³⁻⁵⁾, prior austenite (hereafter referred to as prior γ) grain size⁶⁻⁹⁾, and compressive residual stress^{10, 11)}. Nakanishi et al.⁵⁾ reported that the grain boundary oxidation layer serves as a fatigue failure initiation point based on observations of fracture surfaces after fatigue testing of steel rods subjected to gas carburizing.

To prevent grain boundary oxidation during carburizing, the vacuum carburizing process has been developed and is increasingly utilized in industry^{12, 13)}. Morita et al.¹⁴⁾ conducted experiments comparing gas carburizing and vacuum carburizing on low carbon steel, reporting that while excessive carburizing can lead to carbide precipitation at grain boundaries and reduce fatigue strength, vacuum carburized steel exhibits higher fatigue strength under conditions that do not promote excessive carburizing.

This study aims to explore the mechanisms for improving plane bending fatigue strength in vacuum carburized low carbon steel. Among the various factors influencing fatigue strength, prior γ grain size is of particular interest because it can be controlled by adjusting the quenching temperature. Quenching temperature is an industrially practical parameter that can be modified relatively easily during heat treatment processes. If fatigue strength can be improved by optimizing prior γ grain size through quenching temperature control, this would provide significant industrial value for enhancing the durability of automotive components without major changes to existing manufacturing systems. Spe-

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cifically, we focus on clarifying the impact of refining the prior γ grain size on fatigue strength, conducting experiments using specimens prepared under various quenching temperature conditions. Fatigue tests were performed on steel plates subjected to quenching after vacuum carburizing, and the relationship between grain size and fatigue strength was evaluated through observations of fracture morphology.

2. Experimental methods

2.1 Materials

The test materials consisted of hot-rolled steel plates with a thickness of 2.8 mm and a composition shown in **Table 1**, which underwent spheroidizing annealing. Plane bending fatigue test specimens were extracted with dimensions shown in **Fig. 1**. The fatigue specimens were hourglass shaped with a curvature radius of 40 mm, and the width of the necked section was 20 mm, with a surface finish precision of Ra 1.6 μm .

Figure 2 shows the vacuum carburizing and quenching conditions. The vacuum carburizing was performed by Onex Co., achieving a surface carbon concentration of $0.60 \pm 0.05\%$. The carburizing temperature was set at 870°C for a duration of 75 min, controlling the effective hardening depth (the thickness of the surface hardened layer with a Vickers hardness of 550 or higher) to be

between 0.35 and 0.40 mm. After vacuum carburizing, the temperature was reduced to 860°C and held for 30 min before air cooling. The heat treatment at 860°C was not based on material considerations but was conducted due to equipment constraints.

Following vacuum carburizing, quenching treatment was performed using a Nisshin Kanetsu Kogyo Co. manufactured NiCE Toolmaster alumina fluidized bed furnace and oil at 70°C . The quenching temperature (T_Q) was varied between 820°C and $1\,030^\circ\text{C}$, with a holding time of 3 min before immersion in the 70°C oil for oil quenching.

2.2 Prior γ grain size, hardness distribution, and residual stress of specimens

From one of the fatigue tests conducted on vacuum carburized and quenched specimens, samples were extracted to observe the necked section's width cross-section, measuring the prior γ grain size and hardness distribution. The samples were polished to a mirror finish and treated with a mixture of saturated picric acid solution, surfactant, and oxalic acid to reveal the prior γ grain boundaries. These were observed using a Keyence Co. laser microscope VK-X110, and the average prior γ grain size was determined using the JIS G 0551 method. The measurement area was set to a surface depth of 100 μm and a width of 1 000 μm in the specimen.

Additionally, approximately ten coarse prior γ grains were visually selected from the measurement area, and their length of long and short axes were measured to calculate the equivalent circular diameter by averaging the lengths and multiplying by $4/\pi$. The maximum size of the coarse prior γ grains was defined as the maximum prior γ grain size of the specimen.

Hardness was measured using a Vickers hardness test with a load of 0.2 kg, taken from the surface to a depth of 0.1 mm in 0.1 mm increments, allowing for the determination of surface hardness, effective hardening depth, and internal hardness. Surface hardness was calculated as the arithmetic mean of the Vickers hardness at 0.1 mm from both side of the surface, while internal hardness was the arithmetic mean of the Vickers hardness from ± 0.2 mm from the center of the plate thickness.

Residual stress at the center of the specimen width in the longitudinal direction (load direction in fatigue test) was measured on both side of the surface of the specimens using a Pulstec Industrial Co. portable X-ray residual stress measurement device μ -X360. The residual stress was averaged from three measurements taken on both side of the surface. The measurement was performed using the $\cos \alpha$ method with the following conditions: X-ray tube: Cr, voltage: 30 kV, current: 1.0 mA.

Table 1 Chemical composition of steel (mass%)

Steel	C	Si	Mn	P	S	Others
J	0.14	0.25	0.35	0.005	0.004	Cr, B, Sb

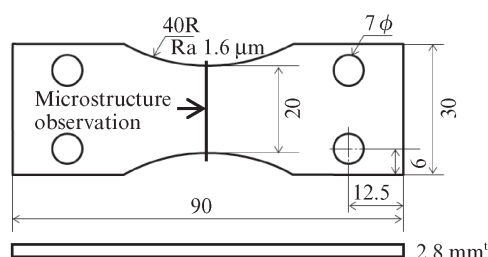


Fig. 1 Specimen for plane bending fatigue test

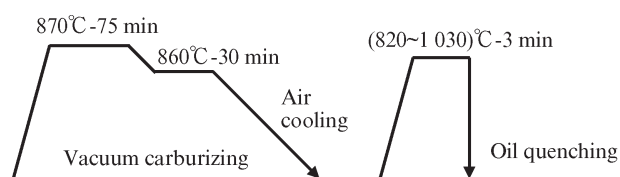


Fig. 2 Thermal history of vacuum-carburizing and quenching

2.3 Fatigue testing

Fatigue tests were conducted using a Tokyo Koki Co. plane bending fatigue testing machine PBF-60Xa. The tests were performed at a frequency of 25 kHz with a stress ratio of -1 . Fracture determination was based on a reduction in moment, with a fracture being defined when the moment decreased by 3 N·m from the initial moment. The fatigue strength was determined with a maximum number of cycles set at 1×10^7 .

3. Results

3.1 Properties of vacuum carburized and quenched materials

Figure 3 presents optical microscope images of the surfaces of specimens quenched at $T_Q = 820^\circ\text{C}$ to $1\,030^\circ\text{C}$. **Figure 4** shows the relationship between quenching temperature and average and maximum prior γ grain sizes. Both average and maximum grain sizes decreased with lower quenching temperatures.

Table 2 summarizes the specimen preparation conditions and the measured results of specimen properties.

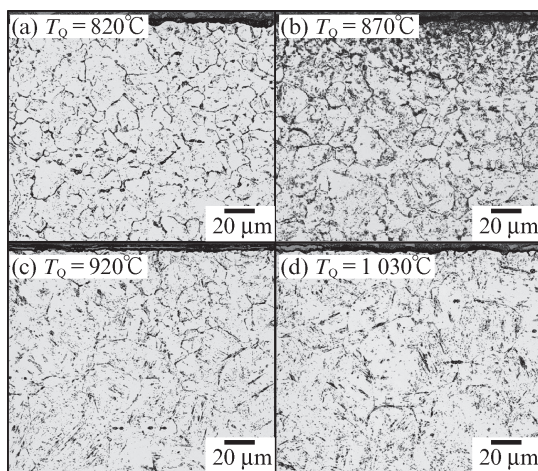


Fig. 3 Optical microstructures of austenite grains after carburized and quenched at each temperature

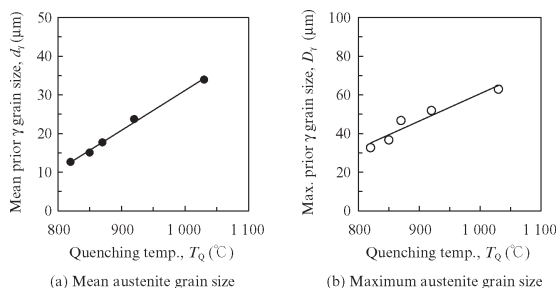


Fig. 4 Relation between austenite grain size and quenching temperature

The surface hardness of all specimens exceeded 760 HV. Residual stress was approximately -350 MPa compressive residual stress in the direction of the fatigue test load for all specimens.

3.2 Fatigue test results

Figure 5 presents the S-N curve for the steel sheets after vacuum carburizing and quenching. The specimen with the highest quenching temperature, JE, exhibited low fatigue strength at 1×10^7 cycles, while quenching conditions that refined the prior γ grain size resulted in higher fatigue strength.

Figure 6 shows the fracture initiation point of a fatigue specimen that failed at a stress amplitude of 800 MPa. The specimen JA ($T_Q = 820^\circ\text{C}$) with a maximum prior γ grain size D_γ of $33\ \mu\text{m}$ exhibited transgranular fracture surface. The specimen JB ($T_Q = 850^\circ\text{C}$) also exhibited transgranular fracture. In contrast, specimens JC ($T_Q = 870^\circ\text{C}$), JD ($T_Q = 920^\circ\text{C}$), and JE ($T_Q = 1\,030^\circ\text{C}$) with D_γ larger than $47\ \mu\text{m}$ showed intergranular fracture. Naito et al.¹⁵⁾ and Ochi et al.¹⁶⁾ have also reported the presence of intergranular

Table 2 List of quenching condition, hardness and residual stress

Steel No.	JA	JB	JC	JD	JE
Quench temp. ($^\circ\text{C}$)	820	850	870	920	1 030
Case hardness (HV200 g)	769	773	834	797	768
Core hardness (HV200 g)	240	242	270	368	384
Effective case depth (mm)	0.35	0.40	0.35	0.40	0.40
Residual stress (MPa)	-322	-292	-336	-358	-437

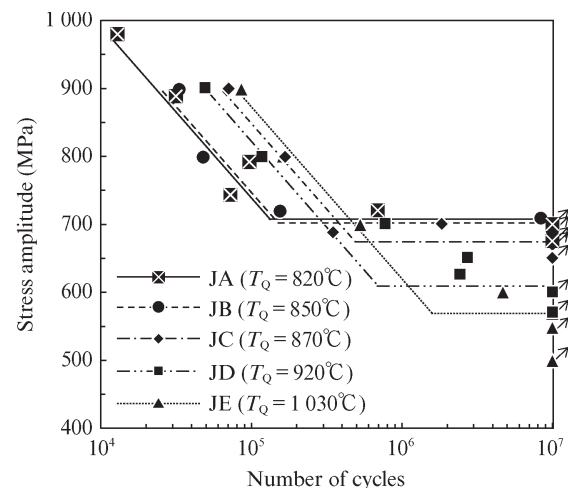


Fig. 5 S-N curves of plane bending fatigue test

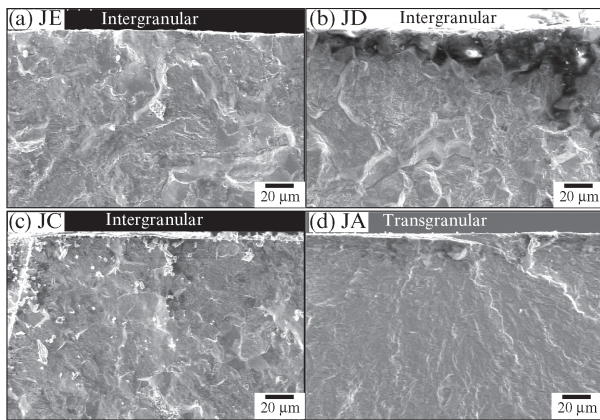


Fig. 6 Fractographs of crack initiation sites of fatigue fractured specimens

fracture surfaces as fatigue failure initiation points in carburized steels.

4. Discussion

4.1 Fatigue failure process of vacuum carburized steel sheets

For the specimen JE ($T_Q = 1\,030^\circ\text{C}$) where intergranular fracture surfaces were observed, cross-sectional observations were conducted. **Figure 7** shows a longitudinal cross-section near the fracture of a specimen that failed at a stress amplitude of 800 MPa. The horizontal direction of the image represents the stress load direction, while the vertical direction represents the sheet thickness direction. In **Fig. 8**, cracks along the prior γ grain boundaries were observed. These intergranular fracture cracks occurred perpendicular to the stress load direction and are believed to have been induced by the loading stress during the fatigue test. Conversely, no cracks were observed in the 45° direction within the grains. Thus, in specimens indicating fatigue failure initiation at intergranular fracture surfaces, it is inferred that cracks along the prior γ grain boundaries develop prior to the typical intragranular fatigue failure caused by the accumulation of dislocation slip.

The authors estimated the fatigue failure process when intergranular fracture occurs and the relationship between grain size and fatigue strength, as shown in **Fig. 8**. In intergranular fatigue failure, cracks initially develop along the prior γ grain boundaries, behaving as initial cracks, which then propagate as fatigue cracks within the grains.

The relationship between the initial crack length a and fatigue strength σ_w in the presence of an initial crack is given by the following equation¹⁷⁾, where K_{th} is

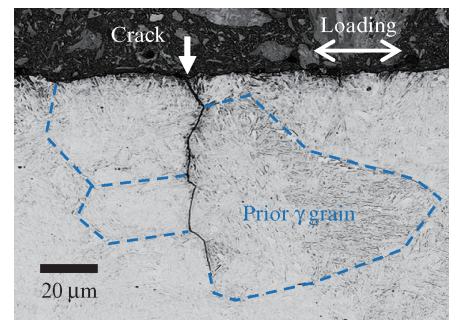
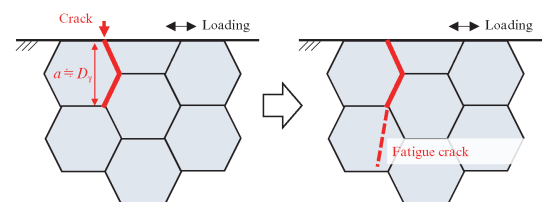


Fig. 7 Cross sectional micrograph of fatigue specimen (JE)

(a) Intergranular fatigue fracture

1. Intergranular fracture occurs during cyclic loading, and it acts as a pre-existing crack
2. The pre-existing crack propagates into the grain as a fatigue crack



(b) Typical fatigue fracture (Transgranular fatigue fracture)

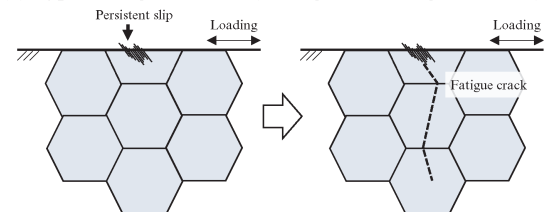


Fig. 8 Effect of grain size on intergranular fatigue fracture

the lower limit of the stress intensity factor range. The K_{th} value for martensitic steel has been reported to be between $4\text{ MPa}\cdot\text{m}^{1/2}$ and $10\text{ MPa}\cdot\text{m}^{1/2}$ ¹⁸⁾.

$$\sigma_w = K_{th} / \sqrt{\pi a} \quad \dots\dots\dots (1)$$

On the other hand, in the case of transgranular fatigue failure caused by the accumulation of dislocation slip, a Petch-type relationship is said to exist between grain size d and fatigue strength σ_w , given by the following equation with k_f as a material constant¹⁹⁾.

$$\sigma_w = \sigma_0 + k_f / \sqrt{d} \quad \dots\dots\dots (2)$$

Izumida et al.²⁰⁾ investigated the dependence of fatigue strength on prior γ grain size in TS 2 000 MPa class oil-tempered wire with a tempered martensitic structure having a chemical composition of 0.65C-1.95Si. They reported that reducing the average prior γ grain size from $20\text{ }\mu\text{m}$ to $4\text{ }\mu\text{m}$ improved fatigue strength from 770 MPa to 890 MPa. Although Izumida et al.²⁰⁾ did not mention fatigue failure morphology, it

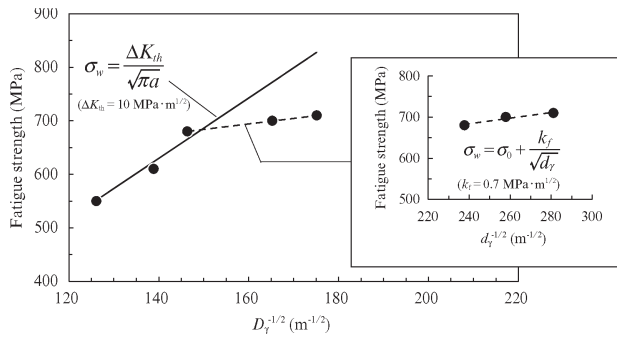


Fig. 9 Relation between fatigue strength and prior austenite grain size

can be inferred from their discussion that the fatigue failure was due to transgranular fracture caused by dislocation slip. Calculating k_f from Izumida et al.'s results yields a value of $0.5 \text{ MPa}\cdot\text{m}^{1/2}$.

Figure 9 shows the relationship between fatigue strength and maximum prior γ grain size D_γ . The horizontal axis is set to D_γ because the initial crack length caused by intergranular fracture is approximately equivalent to the size of one prior γ grain, and it is assumed that the longest initial crack will grow into a fatigue crack. As D_γ becomes finer, fatigue strength increases; however, when D_γ is less than $47 \mu\text{m}$, the increase in fatigue strength becomes minimal. The point where D_γ is $33 \mu\text{m}$ indicates a specimen exhibiting transgranular fatigue failure.

The plots in Fig. 9 with D_γ greater than $47 \mu\text{m}$ indicate that intergranular fracture surfaces were observed at the fracture initiation point. The slope of the specimens showing intergranular fracture surfaces closely matched the slope $K_{th}/\sqrt{\pi}$ when the initial crack length a was set to D_γ and $K_{th} = 10 \text{ MPa}\cdot\text{m}^{1/2}$ (as reported by Murakami et al.¹⁸). This result supports the estimation of the fatigue process shown in Fig. 9.

Next, for the three points $D_\gamma = 47 \mu\text{m}$, $D_\gamma = 37 \mu\text{m}$, and $D_\gamma = 33 \mu\text{m}$, the slope k_f was determined when the horizontal axis was set to the average prior γ grain size d_γ , yielding a value of $0.7 \text{ MPa}\cdot\text{m}^{1/2}$. This is nearly consistent with the k_f value of $0.5 \text{ MPa}\cdot\text{m}^{1/2}$ obtained from the results reported by Izumida et al.²⁰.

From the above, it can be concluded that as the prior γ grain size becomes finer, the increase in fatigue strength diminishes because the fatigue failure initiation point shifts from intergranular to transgranular. This transition occurs because the initial cracks become small enough that they do not significantly affect fatigue failure, resulting in the occurrence of typical transgranular fatigue failure due to the accumulation of dislocation slip.

5. Conclusion

To explore guidelines for improving fatigue strength in the vacuum carburizing and quenching process, we conducted vacuum carburizing on low carbon steel and evaluated its plane bending fatigue strength. The primary objective was to clarify the impact of refining the prior γ grain size on fatigue strength. Specimens were prepared under different quenching temperature conditions after vacuum carburizing, and fatigue tests were conducted, yielding the following results:

- (1) By performing quenching at temperatures ranging from 820°C to 1030°C after vacuum carburizing, specimens with a maximum prior γ grain size D_γ of 33 to $63 \mu\text{m}$ and an average prior γ grain size d_γ of 13 to $34 \mu\text{m}$ were produced. The same conditions were used for vacuum carburizing, and there were no significant differences in case hardness, effective hardening depth, or residual stress among the samples.
- (2) The plane bending fatigue strength of vacuum carburized low carbon steel improves with the refinement of prior austenite grain size. When the maximum prior austenite grain size exceeds $47 \mu\text{m}$, fatigue failure occurs due to intergranular fracture. When the maximum prior austenite grain size is $47 \mu\text{m}$ or less, fatigue failure occurs due to typical transgranular fracture. Correspondingly, when the maximum prior austenite grain size is $47 \mu\text{m}$ or less (with an average grain size of $18 \mu\text{m}$ or less), the increase in fatigue strength due to the refinement of prior austenite grains becomes minimal.

These results indicate that in vacuum carburized and quenched components, as the prior γ grain size becomes coarser, fatigue failure occurs due to intergranular fracture, and the impact of variations in prior γ grain size on fatigue strength becomes significant. Conversely, by refining the prior γ grain size to the point where the fatigue failure initiation point shifts to transgranular fracture, the influence of variations in prior γ grain size on fatigue strength diminishes, suggesting that high fatigue strength can be consistently achieved.

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