NIMS fatigue data sheet on gigacycle fatigue properties of SCr420 (0.20C-1.05Cr) carburizing steel for machine structural use

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ABSTRACT
The new fatigue data sheet, No. 131, discloses gigacycle fatigue properties of the carburizing steel tested under rotating-bending conditions. This fatigue data sheet employed vacuum carburizing, as well as gas carburizing. Both as carburized and polished specimens were tested. In case of the polished specimens, two conditions of hardened layer depths were applied, i.e. deep and shallow cases. The fatigue test results demonstrated that gigacycle fatigue took place in the carburizing steel. Many specimens failed at over $10^7$ cycles, ending in internal fractures. The origins of the internal fractures were oxide-type inclusions located in or beneath the hardened layer. The as carburized specimens of the vacuum carburizing revealed higher fatigue strength than those of the gas carburizing. One of the reasons of this improvement was fine microstructures created by the vacuum carburizing at around the surfaces. The polished specimens showed further high fatigue strength, developing more internal fractures. The deep case then revealed higher fatigue strength than the shallow case. In case of surface fractures, typical fatigue fracture surfaces were not observed, i.e. only intergranular fracture surfaces were observed in the hardened layers. Fish-eye patterns were observed in case of the internal fractures, while outsides of the fish-eye patterns were the intergranular fracture surfaces. Our interpretation was that the hardened layers were too brittle to allow conventional fatigue crack growth. In other word, the hardened layers were brittle-fractured immediately after the crack initiation, or only internal fatigue crack growth were allowed.

1. Introduction
NIMS fatigue data sheets comprise a huge database of fatigue properties of structural materials [1]. The total number of fatigue data sheets is 131 (Nos. 0–130) to date and is still increasing. This paper introduces a new fatigue data sheet designated as No. 131.

This fatigue data sheet discloses gigacycle fatigue properties of carburizing steel tested under rotating-bending conditions. Former fatigue data sheets of Nos. 37, 43, 50 and 51 had already disclosed conventional high-cycle fatigue properties of the carburizing steels [2–5], while industries continuously requested the gigacycle version. The gigacycle fatigue tests up to over $10^9$ cycles were thus conducted for the carburizing steel.

The former fatigue data sheets adopted only gas carburizing, while this version adopted vacuum carburizing as well as the gas carburizing. Details of the new fatigue data sheet are as follows.

2. Experimental method
2.1. Materials

Tables 1 and 2 show processing details and chemical compositions of the tested steel. The tested steel was hot-rolled round bars of JIS-SCr420 sampled in 2016. Tables 3 and 4 show the carburizing conditions. A condition, ‘deep case’, was applied to the gas carburizing, while two conditions, ‘deep and shallow...

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cases’, were applied to the vacuum carburizing. The deep and shallow cases indicate the depth of the hardened layers.

Figures 1 and 2 show hardness distributions. The hardened layer depth of the deep cases exceeds 1 mm in contrast to the shallow case.
Figures 3 and 4 show residual stress distributions. Peaks of the compressive residual stress are at around 1.0 mm and 0.5 mm in deep and shallow cases, respectively. Figures 5–7 show the microstructures. The vacuum carburizing results in very fine microstructures at around the surfaces, while the gas carburizing reveals abnormal microstructures at around the surface as indicated by a white ellipse in Figure 5.

**Figure 1.** Hardness distribution curves for SCr420 gas carburizing steel specimen of deep case.

**Figure 2.** Hardness distribution curves for SCr420 vacuum carburizing steel specimen.

**Figure 3.** Residual stress distribution curves for SCr420 gas carburizing steel specimen of deep case. Residual stress was measured using X-ray diffraction analysis.

**Figure 4.** Residual stress distribution curves for SCr420 vacuum carburizing steel specimen. Residual stress was measured using X-ray diffraction analysis.
2.2. Fatigue testing

Table 5 shows the fatigue test conditions. Two types of rotating bending machines were used. One was a cantilever type which was applied to the gigacycle fatigue tests. The cantilever type had 48 stations to test many specimens at once, and the gigacycle fatigue tests took almost two years. The other was a 4-point bending type applied to the short life fatigue tests. The capacity of
the cantilever type was too small to be applied to the high stress conditions. This was the reason why the 4-point type was additionally used.

Figure 7. Microstructure of SCr420 vacuum carburizing steel specimen of shallow case.

Table 5. Gigacycle fatigue test conditions.

| Type of test          | Rotating bending                  |
|-----------------------|----------------------------------|
| Type and capacity of testing machine | Cantilever type 50 N·m | 4-point loading type 100 N·m |
| Loading condition     | Constant stress amplitude under zero mean stress |
| Waveform              | Sinusoidal                       |
| Frequency             | 30 Hz and 60 Hz                  | 50 Hz                       |
| Environment           | RT, laboratory air               |
| Specimen (dimensions in mm) | 90% risk volume = 69 mm³ | 90% risk volume = 78 mm³ |

Table 6 shows finishings of the specimen surfaces. Both as carburized and polished specimens were tested. The as carburized specimens were applied to
the deep cases of gas and vacuum carburizing in order to evaluate the effects surface layers. The polished specimens were applied to the deep and shallow cases of vacuum carburizing. Internal fractures were expected in the polished specimens.

### 3. Experimental results

#### 3.1. Fatigue test results

Figure 8 shows the fatigue test results of as carburized specimens. Figure 8(a) is the gas carburized specimens. Many specimens were fractured at over $10^7$ cycles, so the fatigue limit was obscure. Two specimens failed at over $10^9$ cycles. These specimens developed internal fractures originating from oxide-type inclusions in the hardened layer, while other specimens developed surface fractures. Figure 8(b) is the vacuum carburized specimens. Several specimens were fractured at over $10^7$ cycles, while no specimens failed at over $10^8$ cycles. The long-life fatigue failures were thus reduced in the vacuum carburizing. All of the vacuum carburized specimens, then, ended in surface fractures.

Figure 9 shows the fatigue test results of polished specimens. Many specimens were fractured at over $10^7$ cycles, developing the internal fractures. The fatigue limits were thus obscure both in the deep and shallow cases. All of the internal-fractured specimens revealed oxide-type inclusions at the fracture origins. The internal fracture origins were located in or beneath the hardened layers.

#### Table 6. Specimen surface

| Carburizing depth | Specimen surface | Carburizing | Vacuum carburizing | Deep case | Shallow case |
|-------------------|------------------|-------------|--------------------|----------|-------------|
| 1) See Figures 1 and 2 |
| 2) The specimen surfaces were polished with silicon carbide paper, followed by finishing with cloth 1μm diamond paste. The polishing removed about 0.25 μm of the surface layer. |

**Figure 8.** Fatigue test results of as carburized specimens of deep cases. *: Number of overlapped specimens.
Table 7 shows estimated gigacycle fatigue strengths. These are average values between the maximum stress amplitude at which no specimen is fractured and that just above it. The vacuum carburizing shows higher fatigue strength than the gas carburizing under the as carburized conditions. The polished specimens of the vacuum carburizing show further high fatigue strength. In comparison between the deep and shallow cases, the deep case shows higher fatigue strength. As the results, the polished specimens of the vacuum carburizing with the deep case show the highest fatigue strength.

3.2. Fracture surfaces

Figure 10 shows typical fracture surfaces of the surface-fractured specimens. The fracture surfaces near the surfaces revealed the features of intergranular fractures, and those at around the center were dimples. Accordingly, typical fatigue fracture surfaces were not observed. No fish-eye patterns were observed on these fracture surfaces, so these specimens were categorized as the surface-fractured specimens. The intergranular fracture regions were shallow in the specimens of the shallow case. The intergranular fractures occurred in the hardened layers in contrast to ductile fracture in the core regions.

Table 7. Estimated mean fatigue strengths at 1.9 × 10⁹ or 3.5 × 10⁹ cycles (stress amplitude in MPa).

| Carburizing | Gas carburizing | Vacuum carburizing |
|-------------|-----------------|--------------------|
| Specimen surface | As carburized | Deep case |
| Fatigue strength | 3.5 × 10⁹ cycles | As carburized |
|                | 500             | 1.9 × 10⁹ cycles |
|                | 660             | 740 |
|                | 660             | 660 |

1) JIS Z 2274 (1985), "Reference for method of rotating bending fatigue testing of metals".
2) See Figure 1 and 2.
3) See Table 6.
Figure 11 shows typical fracture surfaces of the internal-fractured specimens. The internal-fractured specimens revealed clear fish-eye patterns. Outsides of the fish-eye patterns were the intergranular fracture morphologies in the hardened layers and the dimples in the core regions. When the internal fracture origins were located at far distances from the surfaces, the fish-eye patterns did not touch the surfaces, i.e. there were gaps between the surfaces and the fish-eye patterns. The internal fracture origins were the typical oxide-type inclusions.

4. Discussion

The gigacycle fatigue tests for the carburizing steel demonstrated that many specimens were fractured at over $10^7$ cycles, meaning that the fatigue limits were obscure. This is the first point to be noted in these fatigue test results.

Another unique point of these fatigue tests is employment of the vacuum carburizing. The vacuum carburizing resulted in higher fatigue strength than the gas carburizing. One reason is reduction of internal fractures. Two specimens of the gas carburizing were
internal-fractured at 540 MPa, while no specimen of the vacuum carburizing failed at this stress amplitude. This means that internal fracture strength is increased by the vacuum carburizing since the polished specimens develop the internal fractures at higher stress amplitudes. The other reason is the increase of surface fracture strength. Three specimens of the gas carburizing were surface-fractured at 620 MPa, in contrast to no failure of the vacuum carburizing at this stress amplitude. The reason of increasing the internal fracture strength is unknown, while that of increasing the surface fracture strength is fine microstructures created by the vacuum carburizing at around the surfaces. On the other hand, the polished specimens showed further high fatigue strength. Therefore, there are some other surface effects such as roughness or else.

The fracture surface morphologies are also suggestive. Typical fatigue fracture surfaces were not observed. There were only intergranular fracture

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**Figure 11.** Fracture surfaces of internal-fractured specimens.
morphologies or fish-eye patterns. Our interpretation is that the hardened layers of the carburizing steel are too brittle to allow stable fatigue crack growth. Namely, the hardened layers are brittle-fractured immediately after the crack initiation. When the fatigue cracks initiate at interiors, the fatigue cracks can stably grow because of the vacuum environment. Stress gradients due to the rotating-bending tests may also affect the internal stable crack growth, i.e. stress at internal crack initiation sites is lower than that at the surfaces. The fracture surfaces of the carburizing steel are thus distinctive.

5. Summary

The NIMS fatigue data sheet of No. 131 discloses gigacycle fatigue test results on the carburizing steel under rotating-bending conditions. The vacuum carburizing was then employed as well as the gas carburizing, using both as carburized and polished specimens. The carburizing steel revealed fatigue failure at over $10^7$ cycles, developing the internal fractures. The fatigue limits were thus obscure. The fatigue strength of the vacuum carburizing steel was higher than that of the gas carburizing. The polished specimens showed higher fatigue strength than the as carburized specimens, developing more internal fractures. Typical fatigue fracture surfaces were not observed, i.e. there were only intergranular fracture morphologies or fish-eye patterns. It was likely that the hardened layer was so brittle that brittle fractures occurred immediately after the crack initiation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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