NIMS fatigue data sheet on gigacycle fatigue properties of A6061-T6 (Al-1.0Mg-0.6Si) aluminium alloy at high stress ratios

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ABSTRACT
The new fatigue data sheet, No. 132, discloses gigacycle fatigue properties of the A6061-T6 aluminium alloys at high stress ratios. The fatigue tests were conducted mainly by the ultrasonic fatigue testing at 20 kHz, while conventional fatigue tests at 100 Hz were also conducted for comparison. The fatigue test results indicated that fatigue limits were obscure in the A6061-T6 alloys. Many specimens failed at over $10^7$ cycles, developing internal fractures as well as surface fractures. On the other hand, fatigue failures at over $10^9$ cycles were very rare, suggesting the presence of new fatigue limits in the gigacycle region. The differences in fatigue test results were negligible between the 20 kHz and 100 Hz tests, demonstrating that the 20 kHz tests were comparable to the conventional fatigue tests on this material. The fatigue strengths evaluated by the stress amplitude were decreased according to increase in the stress ratios, while the degradation of the fatigue strengths was not so serious. The fatigue strengths were higher than the modified Goodman lines, meaning that the stress ratio effects could be estimated by conventional ways.

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. 132.

This fatigue data sheet discloses gigacycle fatigue properties of A6061-T6 aluminium alloy at high stress ratios. A series of previous fatigue data sheets had disclosed gigacycle fatigue properties of A5083P-O and A7075-T6 alloys [2–7]. The former data sheets were comprised of three types. The first one was low- and high-cycle fatigue properties tested under strain- and load-control conditions, respectively. The second one was gigacycle fatigue properties tested by rotating-bending and ultrasonic fatigue tests. The third one was gigacycle fatigue properties at high stress ratios. This was also the case of the A6061-T6 alloy, and the low- and high-cycle and the gigacycle versions had already been published [8,9]. This fatigue data sheet is thus the third one of the A6061-T6 series.

The fatigue tests were conducted mainly by the ultrasonic fatigue testing at 20 kHz, while conventional fatigue tests at 100 Hz were also conducted for comparison. The previous fatigue data sheet had demonstrated that the results were comparable between the ultrasonic and conventional fatigue testings [9]. 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 alloys. The tested alloys were a hot-rolled plate and extruded round bars...
sampled in 2017. Table 3 shows the mechanical properties. The tensile strengths of the tested alloys were around 300 MPa, which were close to those of A5083P-O. The mechanical properties of Heat A were disclosed both in longitudinal and in transverse directions, while the anisotropy was very small.

Figures 1 and 2 show the microstructures of the tested alloys. Figure 1 is polarized light images which reveal grain sizes and shapes. Figure 2 is forward light images which reveal distributions of precipitates. The grain sizes of Heat B are finer than those of others. The precipitates are not so dense and the differences between heats are not remarkable.

### 2.2. Fatigue testing

Table 4 shows the fatigue test conditions. Two types of fatigue testing machines were used. One was an electromagnetic resonance type at 100 Hz. The other was the ultrasonic type at 20 kHz. The cutoff cycle numbers were $10^6$ at 100 Hz and $10^{10}$ at 20 kHz. The stress ratios were $R = -1$, 0 and 0.3. In addition to these stress ratio conditions, $\sigma_{\text{max}} = \sigma_{\text{Y}}$ tests were applied. In the $\sigma_{\text{max}} = \sigma_{\text{Y}}$ tests, maximum stresses were fixed at 0.2% proof stresses instead of fixing the stress ratio. The $\sigma_{\text{max}} = \sigma_{\text{Y}}$ test condition corresponds to the highest stress ratio condition, assuming that the materials are used in an elastic region.

### 3. Experimental results

#### 3.1. Fatigue test results

Figures 3 and 4 show the fatigue test results. Many specimens were fractured at over $10^7$ cycles, so the fatigue limits were obscure. Internal fractures occurred in several specimens. The internal fractures were more frequent under high stress ratio conditions. Slight differences were observed in the fatigue strength between the heats. Heats B and C,

### Table 1. Processing details and related properties of A6061-T6 aluminium alloy

| Heat | Forming process | Extrusion ratio | Product form and size (mm) | Heat treatment |
|------|-----------------|----------------|---------------------------|---------------|
| A    | Rolling         | -              | Plate                     | T651          |
| B    | Extruding 23.0  | Bar            | $20 \times 1250 \times 2500$ | T6           |
| C    | Extruding 39.5  | Bar            | $\varphi 18 \times 2000$   | T6           |

*Sampled in 2017. Reported by the manufacturer.

### Table 2. Chemical compositions of A6061-T6 aluminium alloy

| Element (mass %) | Heat | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|------------------|------|----|----|----|----|----|----|----|----|
| A                | 0.57 | 0.39 | 0.26 | 0.02 | 0.94 | 0.11 | 0.01 | 0.04 |
| B                | 0.50 | 0.21 | 0.32 | 0.03 | 1.00 | 0.06 | 0.02 | 0.01 |
| C                | 0.58 | 0.20 | 0.35 | 0.04 | 1.00 | 0.05 | 0.02 | 0.01 |
| Requirement h,c   | max  | 0.80 | 0.70 | 0.40 | 0.15 | 1.20 | 0.35 | 0.25 | 0.15 |
|                   | min  | 0.40 | -   | 0.15 | -   | 0.80 | 0.04 | -   | -   |

*Reported by the manufacturer.

### Table 3. Mechanical properties of A6061-T6 aluminium alloy

| Heat | Sampling direction of specimen | 0.2% proof stress (MPa) | Tensile strength (MPa) | Elongation (%) | Reduction of area (%) | Vickers hardness (HV/98N) |
|------|--------------------------------|------------------------|------------------------|----------------|-----------------------|---------------------------|
| A    | Longitudinal                   | 293                    | 306                    | 15             | 51                    | 112                       |
|      | Transverse                     | 284                    | 309                    | 14             | 46                    | 112                       |
|      | Requirement b                  | min 245                | min 294                | min 9          | -                      | -                         |
| B    |                                | 277                    | 308                    | 15             | 60                    | 107                       |
| C    |                                | 260                    | 295                    | 16             | 58                    | 104                       |
|      | Requirement c                  | min 240                | min 260                | min 10         | -                      | -                         |

*JIS Z 2241 (2011), No.14A type specimen with 8 mm diameter and 40 mm gage length.
The nominal strain rate of the specimen was controlled to 0.00025 s$^{-1}$.
*JIS H 4000 (2014), 'Aluminium and aluminium alloy sheets, strips and plates'.
*JIS H 4040 (2015), 'Aluminium and aluminium alloy bars and wires'.
### Table 4. Fatigue test conditions.

| Type and capacity of testing machine | Electromagnetic resonance type, 100 kN | Ultrasonic type\(^a\), 40–1000 MPa |
|-------------------------------------|----------------------------------------|----------------------------------|
| **Type of test**                    | Uniaxial loading                        |                                 |
| **Loading condition**               | Constant stress amplitude               |                                 |
|                                    | Stress ratios (\(R\)) : −1, 0, 0.3      |                                 |
|                                    | Stress ratios (\(R\)) : 0.27–0.73      |                                 |

\(\sigma_{\text{max}}\) = \(\sigma_Y\)

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} = \frac{\sigma_Y - 2\sigma_k}{\sigma_Y} \]

- **Waveform**: Sinusoidal
- **Frequency**: 100 Hz
- **Environment**: RT (20–28°C), laboratory air
- **Sampling direction**: Heat A: Longitudinal and transverse
- **Specimen\(^c\)**:
  - Dimensions in mm:
  - \(41.2 \times 6.1 \times 16\) mm

\(^a\)In the 20 kHz tests, specimens were air cooled using a heat exchanger and 5.5 kW compressor (60ℓ/min), therefore, the temperature rises of the specimen were less than 10°C.

\(^b\)Under the condition fixing the maximum stress at the 0.2% proof stress.

\(^c\)Surface finishing was performed by longitudinal polishing with 600 grade silicon carbide paper.
Table 5. Estimated mean fatigue strengths\(^a\) at \(10^7\), \(10^8\) and \(10^{10}\) cycles in the case of A6061-T6 aluminium alloy (stress amplitude in MPa).

| Heat          | Sampling direction for specimen | Stress ratio | \(10^7\) cycles\(^b\) Electromagnetic (100 Hz) | \(10^8\) cycles\(^c\) Electromagnetic (100 Hz) | \(10^{10}\) cycles\(^d\) Ultrasonic (20 kHz) |
|---------------|--------------------------------|--------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| A(T651)       | Longitudinal                   | \(R = -1\)  | 90                                           | 75                                            | 75                                            |
|               |                                | \(R = 0\)    | 85                                           | 75                                            | 65                                            |
|               |                                | \(R = 0.3\)  | 75                                           | 65                                            | 55                                            |
|               |                                | \(R = 0.32-0.73\) | 65 | 55 | 45 |
|               | Transverse                     | \((\sigma_{\text{max}} = \sigma_y)\) | \(R = 0.56\) | \(R = 0.63\) | \(R = 0.70\) |
|               |                                | \(R = -1\)  | 110                                          | 75                                            | 75                                            |
|               |                                | \(R = 0\)    | 95                                           | 75                                            | 65                                            |
|               |                                | \(R = 0.3\)  | 85                                           | 75                                            | 65                                            |
|               |                                | \(R = 0.29-0.72\) | 75 | 55 | 45 |
| B(T6511)      |                                | \((\sigma_{\text{max}} = \sigma_y)\) | \(R = 0.47\) | \(R = 0.61\) | \(R = 0.69\) |
|               |                                | \(R = -1\)  | 130                                          | 105                                           | 95                                            |
|               |                                | \(R = 0\)    | 110                                          | 85                                            | 75                                            |
|               |                                | \(R = 0.3\)  | 95                                           | 85                                            | 75                                            |
|               |                                | \(R = 0.28-0.57\) | 95 | 75 | 65 |
| C(T6511)      |                                | \((\sigma_{\text{max}} = \sigma_y)\) | \(R = 0.32\) | \(R = 0.46\) | \(R = 0.53\) |
|               |                                | \(R = -1\)  | 110                                          | 85                                            | 85                                            |
|               |                                | \(R = 0\)    | 110                                          | 85                                            | 85                                            |
|               |                                | \(R = 0.3\)  | 95                                           | 85                                            | 75                                            |
|               |                                | \(R = 0.27-0.54\) | 85 | 75 | 65 |
|               |                                | \((\sigma_{\text{max}} = \sigma_y)\) | \(R = 0.35\) | \(R = 0.42\) | \(R = 0.49\) |

\(^a\)JIS Z 2274 (2006); Reference for method of rotating bending fatigue testing of metals.

\(^b\)Fatigue strength at \(10^7\) cycles were estimated from the data obtained by electromagnetic resonance type machine.

\(^c\)Fatigue strength at \(10^8\) cycles were estimated from the data obtained by electromagnetic resonance type machine.

\(^d\)Fatigue strength at \(10^{10}\) cycles were estimated from the data obtained by ultrasonic-type machine.
Figure 1. Microstructures of A6061-T6 aluminium alloy observed by polarized light.
Figure 2. Microstructures of A6061-T6 aluminium alloy observed by forward light.
which were extruded round bars, revealed slightly higher fatigue strength than the hot-rolled plate of Heat A.

Figure 5 shows S-N diagrams to compare the results between frequencies and stress ratios. The differences between the 100 Hz and 20 kHz tests were negligible, meaning that the 20 kHz tests were comparable to the 100 Hz tests. The fatigue strengths evaluated by the stress amplitudes were lower under high stress ratio conditions, while the degradations were not so remarkable. The fatigue failures at over $10^9$ cycles were very rare. This suggested the presence of new fatigue limits [10] in the gigacycle region.

Table 5 shows estimated mean fatigue strengths at $10^7$, $10^8$ and $10^{10}$ cycles. The mean fatigue strengths are average values between the maximum stress amplitude at which no specimen is fractured and that just above it. The fatigue strengths decrease according to the increase in the cycle numbers. The decreases are larger between $10^7$ and $10^8$ cycles than between $10^8$ and $10^{10}$ cycles.

Figure 6 shows comparison of fatigue strength at $10^7$ and $10^{10}$ cycles among A6061-T6 and other materials. In general, there are linear relationships between the fatigue strength $\sigma_W$ and the tensile strength $\sigma_B$. The relationships under $R = > -1$ are $\sigma_W = 0.53\sigma_B$ for the quenched and tempered (QT) steels and $\sigma_W = 0.39\sigma_B$ for the austenitic stainless steels and the normalized (N) steels. The fatigue strength at $10^{10}$ cycles of A6061-T6 is lower than $\sigma_W = 0.39\sigma_B$ as in the case of A7075-T6. On the other hand, the fatigue strength at $10^7$ cycles is almost equal to $\sigma_W = 0.39\sigma_B$. These indicate that the conventional high-cycle fatigue properties of A6061-T6 are

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**Figure 3.** Fatigue test results obtained at 100 Hz.

**Figure 5.** S-N diagrams to compare the results between frequencies and stress ratios.

**Figure 6.** Comparison of fatigue strength at $10^7$ and $10^{10}$ cycles among A6061-T6 and other materials.
close to those of the austenitic stainless steels and the normalized steels, while the fatigue strength is reduced in the gigacycle region. This is also the case of \( R = 0 \).

Figure 7 shows endurance limit diagrams. The endurance limit diagrams compare the fatigue strengths of A6061-T6 with modified Goodman lines. The fatigue strengths of A6061-T6 are higher than those of the modified Goodman lines.

### 3.2. Fracture surfaces

Figure 8, Figure 9, Figure 10, Figure 11 show typical fracture surfaces. Both the surface and internal fractures are observed, while fish-eye patterns are not clear even in the case of the internal fractures. In several internal-fractured specimens, precipitates are observed at around the fracture origins. The precipitates are Al-Mg-Si or Al-Fe-Si types. It is, however, unknown whether these precipitates affect the internal crack initiation or not. The differences of fracture surfaces are negligible between frequencies and between stress ratios.

### 4. Discussion

The fatigue test results at 20 kHz were comparable to those at 100 Hz. The 20-kHz fatigue testing is thus applicable to this material. This is the first point to be noted in these fatigue test results.

The second point is that the fatigue limits are obscure in A6061-T6. The former fatigue data sheets [3,4,6,7] demonstrated that the fatigue limits were clear in A5083P-O but not in A7075-T6. The tensile strengths of A6061-T6 are close to those of A5083P-O, while the heat treatment, T6, is close to that of A7075-T6. This means that the heat treatment had more effects on the fatigue limits than the tensile strength. In other words, the fatigue limits are obscure in the “T6” materials, while they are clear in the ‘O’ materials.

The third point is that the gigacycle fatigue strengths of A6061-T6 are higher than the modified Goodman lines. This means that the stress ratio effects are not so serious on A6061-T6, unlike Ti-6Al-4 V alloys. In the case of the Ti-6Al-4 V alloys,
the stress ratio effects were so large that the giga-cycle fatigue strengths were lower than the modified Goodman lines at around $R = 0$ [11–13]. These serious stress ratio effects are not observed in A6061-T6. This is also the case of A7075-T6 [7]. In the case of A5083P-O, the fatigue strengths were lower than the modified Goodman lines, while in those cases, the maximal stress exceeded the 0.2% proof stresses. Namely, the fatigue strengths of A5083P-O were close to the yield limits in the
Figure 7. Endurance limit diagram.

Figure 8a. Fracture surfaces at 100 Hz at $R = 0$.

(a) Heat A, Longitudinal, Surface fracture, $\sigma_s = 80$ MPa, $N_f = 2.83 \times 10^6$ cycles

(b) Heat A, Transverse, Surface fracture, $\sigma_s = 90$ MPa, $N_f = 4.24 \times 10^6$ cycles

(c) Heat A, Transverse, Internal fracture, $\sigma_s = 100$ MPa, $N_f = 6.38 \times 10^6$ cycles
Figure 8b. Continued.

(d) Heat B, Surface fracture, $\sigma_s = 90$ MPa, $N_f = 8.40 \times 10^7$ cycles

(e) Heat C, Surface fracture, $\sigma_s = 90$ MPa, $N_f = 6.19 \times 10^7$ cycles

(f) Heat C, Internal fracture, $\sigma_s = 100$ MPa, $N_f = 1.67 \times 10^7$ cycles

EDS: Al > Mg > Si
Figure 9a. Fracture surfaces at 100 Hz under $\sigma_{\text{max}} = \sigma_y$. 

(a) Heat A, Longitudinal, Internal fracture, $\sigma_r = 80$ MPa, $N_f = 2.04 \times 10^6$ cycles

(b) Heat A, Transverse, Surface fracture, $\sigma_c = 100$ MPa, $N_f = 2.19 \times 10^6$ cycles

(c) Heat A, Transverse, Internal fracture, $\sigma_c = 70$ MPa, $N_f = 1.04 \times 10^6$ cycles
Figure 9b. Continued.
Figure 10a. a Fracture surfaces at 20 kHz at $R = 0$. 

(a) Heat A, Longitudinal, Surface fracture, $\sigma = 70$ MPa, $N_r = 1.97 \times 10^6$ cycles

(b) Heat A, Longitudinal, Internal fracture, $\sigma = 90$ MPa, $N_r = 1.14 \times 10^6$ cycles

(c) Heat A, Transverse, Surface fracture, $\sigma = 70$ MPa, $N_r = 8.34 \times 10^5$ cycles

(d) Heat B, Surface fracture, $\sigma = 80$ MPa, $N_r = 7.84 \times 10^5$ cycles

(e) Heat C, Surface fracture, $\sigma = 90$ MPa, $N_r = 2.72 \times 10^6$ cycles
Figure 11a. Fracture surfaces at 20 kHz under $\sigma_{\text{max}} = \sigma_y$. 

(a) Heat A, Longitudinal, Surface fracture, $\sigma = 70$ MPa, $N_r = 4.2 \times 10^6$ cycles

(b) Heat A, Longitudinal, Internal fracture, $\sigma = 50$ MPa, $N_r = 2.9 \times 10^6$ cycles

(c) Heat A, Transverse, Surface fracture, $\sigma = 70$ MPa, $N_r = 2.4 \times 10^6$ cycles

(d) Heat A, Transverse, Internal fracture, $\sigma = 60$ MPa, $N_r = 7.7 \times 10^6$ cycles
endurance limit diagram [4]. In conclusion, the stress ratio effects on A6061-T6 can be estimated by conventional ways, such as modified Goodman lines, as on A7075-T6. In other words, the stress ratio effects on A6061-T6 are normal, while those on Ti-6Al-4 V alloys are abnormal.

5. Summary

The NIMS fatigue data sheet of No. 132 discloses gigacycle fatigue test results on the A6061-T6 aluminium alloys at high stress ratios. The fatigue tests were conducted both by ultrasonic fatigue testing at

Figure 11b. Continued.
20 kHz and by conventional fatigue testing at 100 Hz. Many specimens were fractured at over $10^7$ cycles, indicating that the fatigue limits were obscure in the A6061-T6 alloys. The differences between the 100 Hz and 20 kHz tests were negligible, so the 20 kHz tests were comparable to the 100 Hz tests. The fatigue strengths evaluated by the stress amplitudes were decreased according to increase in the stress ratios, while the stress ratio effects could be estimated by conventional ways such as modified Goodman lines.

**Disclosure statement**

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

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