Catalogue of NIMS fatigue data sheets

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ABSTRACT
This paper summarizes the NIMS fatigue data sheets and makes a new gateway available to access them. The NIMS fatigue data sheets are a huge database of the fatigue properties of structural materials. This project covers fundamental fatigue properties at room temperature and at high temperatures, and the fatigue properties of welded joints. The fundamental fatigue properties recorded include high-cycle, low-cycle and gigacycle fatigue test results for steels, aluminium alloys, titanium alloys and so on. The high-cycle fatigue test results determine the fatigue limits. The low-cycle fatigue test results reveal not only the fatigue lives but also cyclic stress-strain curves. The gigacycle fatigue tests were conducted at 100 Hz for three years up to $10^{10}$ cycles, as well as at 20 kHz for a week. The fatigue properties at high temperatures were evaluated chiefly for steels, via low and high-cycle fatigue tests. The low-cycle fatigue tests were conducted by employing various strain rates and waveforms. The fatigue properties of welded joints were evaluated using thick plates of steels and aluminium alloys, conducting high-cycle fatigue and crack propagation tests employing large specimens in as-welded condition. The high-cycle fatigue tests were conducted using various specimen sizes, welding procedures, stress ratios and so on. The crack propagation tests were conducted for the base metal, the weld metal and the heat-affected zone. Many new findings were obtained with these fatigue data as reviewed in this paper.

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1. Introduction
NIMS fatigue data sheets comprise a huge database of fatigue properties of structural materials. The total number of fatigue data sheets is 126 to date and is still increasing. They are distributed free of charge as printed documents. Previously, the content could be viewed on the NIMS website, but downloading and printing were prohibited. As of the publication of this review paper, however, the NIMS fatigue data sheets are fully available on the Internet. The fatigue data sheets are temporarily only viewed on ‘MatNavi’ (https://smds.nims.go.jp/fatigue/index_en.html) until the middle of 2020, while they will be fully available on a ‘Materials Data Repository (MDR)’ system managed by NIMS after that.

The first issue of fatigue data sheets was published in 1978, so this undertaking has a history of over 40 years. The following three subjects were initially selected for the project.
(1) The fundamental fatigue properties of metallic materials at room temperature in air.
(2) The fatigue properties of heat-resistant metallic materials at high temperatures.
(3) The fatigue properties of welded joints.

This project was briefly interrupted in 1995, but it was restarted in 1996. After the restart, long-term fatigue was a common theme in each subject. When examining fundamental fatigue properties, for example, the cut-off cycles of the fatigue tests were extended from $10^7$ to $10^{10}$. Although the high-temperature fatigue tests were conducted under strain-controlled conditions in low-cycle regions, the strain-controlled tests were continued up to high-cycle regions of $10^6$ cycles. The fatigue tests for the welded joints were conducted mainly at 10 Hz, so the cut-off cycles were normally $10^5$; these were extended to $10^6$. As a result, the fatigue tests took several months or years.

The materials tested were made in Japan. Most were JIS-grade materials. Specific types of materials were systematically selected to cover the major grades of the materials. They were directly sampled from the manufacturer. All the fatigue tests were conducted by NIMS and its predecessor (NRIM: National Research Institute for Metals). This means that the fatigue test conditions were standardized down to the smallest detail. For example, the same types of testing machines were used, the specimens were machined in the same manner, and all the tests were performed by experienced technicians. As the result, data scattering is very low in the NIMS fatigue data sheets. This is one of the major advantages of this database.

The NIMS fatigue data sheets disclose fatigue test results as numerical data. Numerical data remain fully relevant even if how they are interpreted develops in the light of scientific and technological progress. The fatigue test results were validated by an external technical advisory committee whose members consist of industrial engineers currently active in their field. The technical advisory committee also supports the planning of fatigue tests, and the final form of the fatigue data sheets was validated by an internal editorial committee.

The NIMS fatigue data sheets have thus been produced over a long period and maintain a high level of quality. The contents are reviewed below.

### 2. Content

The published NIMS fatigue data sheets are listed in Tables 1–3. No. 0 of the fatigue data sheets [1] is an explanation of the project and No. 84 [36] is a catalogue of the fatigue data sheets of Nos. 1–83. The general contents are summarized as follows.

#### 2.1. Fundamental fatigue properties at room temperature in air

The major materials tested were carbon steels, low-alloy steels, stainless steels, high-strength steels, aluminium alloys and titanium alloys. In addition to these materials, magnesium alloys and cast irons are included in the fatigue data sheets Nos. 110 and 117, respectively. To evaluate scattering between heats, more than two heats were sampled and tested for each grade of material. Particularly in the early versions of the fatigue data sheets, more than ten heats were tested for each grade. The processing details of each heat are also disclosed in the fatigue data sheets.

These fatigue data sheets disclose both high- and low-cycle fatigue properties. The high-cycle fatigue tests were conducted under load-controlled conditions. These tests include rotating bending fatigue tests, reversed torsion fatigue tests and uniaxial stress fatigue tests. The low-cycle fatigue tests were conducted under strain-controlled conditions. They consisted not only of constant strain amplitude tests to determine fatigue lives but also incremental step tests [127] to clarify cyclic stress-strain curves.

To study long-term fatigue, fatigue tests up to $10^{10}$ cycles, so called gigacycle fatigue tests [128], were conducted on high-strength steels, Ti-6Al-4V alloys and aluminium alloys, since fatigue limits were not confirmed in these materials. Two types of testing methods were then employed. One was rotating bending fatigue testing at 100 Hz, which took three years to reach $10^{10}$ cycles. The other was ultrasonic fatigue testing [129–134] at 20 kHz, which completed the required $10^{10}$ cycles in a week. Frequency effects can be evaluated by comparing the results between these two types of fatigue tests.

#### 2.2. Fatigue properties at high temperatures

The major materials tested were carbon steels, low-alloy steels and stainless steels. A Ni-base alloy is also included in Fatigue Data Sheet No. 113. For high-temperature fatigue tests, a single heat was tested for each grade of the materials, since a greater variety of test conditions is more informative than a greater number of heats. The test conditions consist of temperatures, strain rates, waveforms and so on. The major materials selected were used for pressure vessels.

Although both high- and low-cycle fatigue tests were conducted, the low-cycle fatigue tests under strain-controlled conditions were a major part of the high-temperature fatigue data sheets. The low-cycle fatigue tests consisted of both constant-strain amplitude tests and incremental step tests. Some of the
Table 1. List of data sheets for fundamental fatigue properties at room temperature.

| No. | Title                                                                 | Reference |
|-----|-----------------------------------------------------------------------|-----------|
| 1   | Fatigue properties of S25C (0.25C) steel for machine structural use    | [2]       |
| 2   | Fatigue properties of S35C (0.35C) steel for machine structural use    | [3]       |
| 3   | Fatigue properties of S45C (0.45C) steel for machine structural use    | [4]       |
| 4   | Fatigue properties of S55C (0.55C) steel for machine structural use    | [5]       |
| 5   | Fatigue properties of SC440 (0.40C-1Cr) steel for machine structural use |          |
| 6   | Fatigue properties of SCM435 (0.35C-1Cr-0.2Mo) steel for machine structural use |          |
| 7   | Fatigue properties of SCM543 (0.39C-1.8Ni-0.8Cr-0.2Mo) steel for machine structural use |          |
| 8   | Fatigue properties of SNCM439 (0.39C-1.8Ni-0.8Cr-0.2Mo) steel for machine structural use |          |
| 9   | Fatigue properties of SUS304 (18C-8Ni) stainless steel for machine structural use |          |
| 10  | Fatigue properties of SUS430 (17C-8Ni) stainless steel for machine structural use |          |
| 11  | Fatigue properties of Ti-6Al-4V (1100 MPa class) titanium alloy         | [10]      |
| 12  | Fatigue properties of Ti-6Al-4V ELI (900 MPa class) titanium alloy      | [11]      |
| 13  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [12]      |
| 14  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [13]      |
| 15  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [14]      |
| 16  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [15]      |
| 17  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [16]      |
| 18  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [17]      |
| 19  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [18]      |
| 20  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [19]      |
| 21  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [20]      |
| 22  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [21]      |
| 23  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [22]      |
| 24  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [23]      |
| 25  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [24]      |
| 26  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [25]      |
| 27  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [26]      |
| 28  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [27]      |
| 29  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [28]      |
| 30  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [29]      |
| 31  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [30]      |
| 32  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [31]      |
| 33  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [32]      |
| 34  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [33]      |
| 35  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [34]      |
| 36  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [35]      |
| 37  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [36]      |
| 38  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [37]      |
| 39  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [38]      |
| 40  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [39]      |
| 41  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [40]      |
| 42  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [41]      |
| 43  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [42]      |
| 44  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [43]      |
| 45  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [44]      |
| 46  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [45]      |
| 47  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [46]      |
| 48  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [47]      |
| 49  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [48]      |
| 50  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [49]      |
| 51  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [50]      |
| 52  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [51]      |
| 53  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [52]      |
| 54  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [53]      |
| 55  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [54]      |
| 56  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [55]      |
| 57  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [56]      |
| 58  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [57]      |
| 59  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [58]      |
| 60  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [59]      |
| 61  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [60]      |
| 62  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [61]      |
| 63  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [62]      |
| 64  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [63]      |
| 65  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [64]      |
| 66  | Fatigue properties of Ti-6Al-4V (900 MPa class) titanium alloy          | [65]      |

Constant-strain amplitude tests include tension hold-type waveforms, i.e., creep-fatigue tests. The high-cycle fatigue tests were conducted as rotating bending fatigue tests in the early versions, and uniaxial stress fatigue tests were added in the later versions. The temperature conditions, which were determined in accordance with the material’s grades, included not only high temperatures of above 400 °C but also intermediate temperatures of below 400 °C. To investigate long-term fatigue, the strain-controlled fatigue tests were conducted up to high-cycle regions of 10⁹ cycles. In general, the high-cycle fatigue tests were conducted under load-controlled conditions, while the low-cycle fatigue tests were conducted under strain-controlled conditions. The problem was then how to accurately combine these two types of results. The high-cycle fatigue tests under strain-controlled conditions were thus required by...
industry. However, the strain-controlled tests up to $10^6$ cycles took considerable time: for example, several months were necessary to reach $10^6$ cycles.

2.3. Fatigue properties of welded joints

The materials tested were thick plates of carbon steels, low-alloy steels, stainless steels and aluminium alloys. As with the high-temperature fatigue tests, a single heat was tested for each grade of material, since there was a greater demand for a wider range of test conditions. The test conditions included specimen sizes, welding procedures, and stress ratios.

High-cycle fatigue tests and crack propagation tests were conducted using large specimens. Factors affecting the fatigue properties of welded joints were not only their microstructure and hardness but also shape and residual stress. To include the effects of shape and residual stress, the large specimens contained the welded parts in the as-welded state. Figure 1 shows typical specimens used in the high-cycle fatigue tests.

High-capacity fatigue testing machines were needed to test these large specimens.

For long-term fatigue, the high-cycle fatigue tests at 10 Hz were conducted up to $10^8$ cycles, which took several months. The test frequencies for the welded joints ranged from 1–100 Hz and the cut-off cycles were $10^6$ or $10^7$. The fatigue limits were not confirmed by these cut-off cycles, however, so the cut-off cycles were extended. This type of long-term fatigue testing was carried out on non-load-carrying cruciform welded joints of low-alloy steels, to clarify the effects of residual stress and plate thickness.

3. Outcome

3.1. Fundamental fatigue properties at room temperature in air

This series of fatigue data sheets reveals high-cycle fatigue properties, low-cycle fatigue properties and gigacycle fatigue properties. The high-cycle fatigue properties determine the fatigue limits, which are...
Table 3. List of data sheets for fatigue properties of welded joints.

| No. | Title                                                                 | Reference |
|-----|------------------------------------------------------------------------|-----------|
| 5   | Fatigue properties for butt-welded joints of SM50B high tensile steel   | [98]      |
| 11  | Fatigue properties of butt-welded joints of SM50Q rolled steel for welded structure – effect of specimen size - | [99]      |
| 12  | Fatigue properties of butt-welded joints of high strength steel (class 800 N/mm²) for welded structure – effect of specimen size - | [100]     |
| 13  | Fatigue properties of non-load-carrying cruciform welded joints of SM50B rolled steel for welded structure – effect of specimen size - | [101]     |
| 18  | Fatigue properties for load-carrying cruciform welded joints of SM50B rolled steel for welded structure – effect of specimen size - | [102]     |
| 19  | Fatigue properties for butt welded joints of high strength steel (class 800 N/mm²) for welded structure – effect of welding procedure - | [103]     |
| 20  | Fatigue properties for non-load-carrying cruciform welded joints of SM50B rolled steel for welded structure – effect of welding procedure - | [104]     |
| 21  | Fatigue crack propagation properties for butt welded joints of SM50B rolled steel for welded structure – effect of welding procedure - | [105]     |
| 27  | Fatigue properties for butt welded joints of SM50B rolled steel for welded structure – effect of welding procedure - | [106]     |
| 31  | Fatigue crack propagation properties for butt welded joints of high strength steel (class 800 N/mm²) for welded structure – effect of welding procedure - | [107]     |
| 34  | Fatigue properties for butt welded joints of SB42 carbon steel plate for boilers and other pressure vessels – effect of stress ratio - | [108]     |
| 40  | Fatigue crack propagation properties for butt welded joints of SB42 carbon steel plate for boilers and other pressure vessels – effect of stress ration - | [109]     |
| 46  | Fatigue crack propagation properties for butt welded joints of SPV50 (Si-Mn, 500 N/mm² YS) steel plate for pressure vessels – effect of stress ratio - | [110]     |
| 47  | Fatigue properties for weld and HAZ materials of SPV50 (Si-Mn, 500 N/mm² YS) steel plate for pressure vessels | [111]     |
| 53  | Fatigue crack propagation properties for butt welded joints of SUS304-HP (18Cr-8Ni) hot rolled stainless steel plate – effect of stress ratio - | [112]     |
| 54  | Fatigue crack propagation properties for butt welded joints of SUS304-HP (18Cr-8Ni) hot rolled stainless steel plate – effect of stress ratio - | [113]     |
| 57  | Fatigue properties for weld and HAZ materials of SB42 (C-Si, 420 N/mm² TS) carbon steel plate for boilers and other pressure vessels | [114]     |
| 64  | Fatigue properties for butt welded joints of A5083P-O (AI-4.5Mg-0.6Mn) aluminium alloy plates | [115]     |
| 65  | Fatigue properties for weld and base metals of SUS304-HP (18Cr-8Ni) hot rolled stainless steel plate | [116]     |
| 71  | Fatigue properties of butt welded joints of A7NO15-T5 (AI-4.6Zn-1.2Mg) aluminium alloy extruded shapes | [117]     |
| 76  | Fatigue properties for butt welded joints of A7NO1P-T6 (AI-4.5Zn-1.5Mg) aluminium alloy plates | [118]     |
| 80  | Fatigue properties for butt welded joints of A6NO15-T5 (AI-0.6Mg-0.6MnSi) aluminium alloy extruded shapes | [119]     |
| 90  | Fatigue properties of non-load-carrying cruciform welded joints of SM570Q rolled steel for welded structure – effect of residual stress - | [120]     |
| 91  | Fatigue properties of non-load-carrying cruciform welded joints of SM490B rolled steel for welded structure – effect of residual stress - | [121]     |
| 96  | Fatigue properties of non-load-carrying cruciform welded joints of SM490B rolled steel for welded structure – effect of plate thickness (Part 1, thickness 9 mm) - | [122]     |
| 99  | Fatigue properties of non-load-carrying cruciform welded joints of SM490B rolled steel for welded structure – effect of plate thickness (Part 2, thickness 160 mm) - | [123]     |
| 108 | Fatigue properties of non-load-carrying cruciform welded joints of SM490B rolled steel for welded structure – effect of plate thickness (Part 3, thickness 80 mm) - | [124]     |
| 114 | Fatigue properties of non-load-carrying cruciform welded joints of SM490B rolled steel for welded structure – effect of plate thickness (Part 4, thickness 40 mm) - | [125]     |

Figure 1. Typical fatigue test specimens used for welded joints.

The results demonstrated that the fatigue limits are chiefly affected by tensile strength and hardness. Figure 2 shows typical results that indicate the relationship between the fatigue limits and the tensile strengths. The fatigue limits thus increase as a function of tensile strength. This means that the fatigue limits can be estimated if the tensile strength is known. On the other hand, the effects of microstructures can also be seen in Figure 2, i.e., tempered martensite shows superior fatigue limits to ferrite/pearlite. When estimating the fatigue limits, therefore, the microstructural effects should be taken into account.

The high-cycle fatigue properties are also affected by loading modes. Figure 3 shows a comparison of the results between the rotating bending fatigue tests and the uniaxial stress fatigue tests. As seen in Figure 3, rotating bending shows higher fatigue strength than

![Image](distance_between_grips.png)

(a) For butt-welded joints  
(b) For non-load-carrying cruciform welded joints
does uniaxial stress. This difference, which is caused by the effects of stress gradients, is more notable in low-strength materials. In other words, stress gradients have only minor effects in high-strength materials.

The low-cycle fatigue properties chiefly reveal fatigue damage caused by cyclic plastic deformation. Figure 4 shows examples of constant strain amplitude test results. The total strain, which is controlled in low-cycle fatigue tests, is divided into plastic and elastic strains. The high strain regions in which the plastic strains exceed the elastic strains are the low-cycle fatigue regions to which the Manson-Coffin law applies. The low-cycle fatigue regions vary with the ductility of the materials, i.e., the region is wide in ductile materials such as pure titanium, while it is narrow in less ductile materials such as Ti-6Al-4V alloy.

Cyclic stress-strain curves determined by incremental step tests are another important data set in the low-cycle fatigue tests. Cyclic plastic deformation causes microstructural changes, resulting in the occurrence of cyclic softening or hardening. Figure 5 shows examples of cyclic stress-strain curves. Low-strength, ductile materials such as pure titanium frequently reveal cyclic hardening. On the other hand, high-strength and less ductile materials such as Ti-6Al-4V alloy are frequently subject to cyclic softening.

The gigacycle fatigue properties were evaluated for high-strength steels, Ti-6Al-4V alloys and aluminium alloys. Although fatigue cracks normally initiated at surfaces, i.e., surface fractures occurred, the high-strength steels revealed internal fractures when the fatigue limits disappeared. This was also the case for Ti-6Al-4V alloys. Under conditions where internal fractures occurred, ultrasonic fatigue testing showed good agreement with conventional fatigue test results. Figure 6 shows typical results comparing ultrasonic fatigue testing with rotating bending fatigue testing. The rotating bending tests at 100 Hz were conducted for three years to reach $10^{10}$ cycles. The frequency effects are thus negligible under conditions where internal fractures occur, and ultrasonic fatigue testing can therefore be applied to the gigacycle fatigue tests on high-strength steels and Ti-6Al-4V alloys. With aluminium alloys, although internal fractures were rare, ultrasonic fatigue testing results showed good agreement with those of conventional fatigue testing. These results support the use of ultrasonic fatigue testing and contribute to the establishment of a standard for ultrasonic fatigue testing [134].
The gigacycle fatigue properties were also evaluated under high stress ratio conditions. The stress ratio effects need careful attention, particularly with Ti-6Al-4V alloys. Figure 7 shows typical results revealing the stress ratio effects. The Ti-6Al-4V alloys are more prone to internal fractures under high stress ratio conditions, resulting in major degradation of the gigacycle fatigue strengths. As a result, the Ti-6Al-4V alloys showed lower fatigue strengths than their modified Goodman lines. In general, modified Goodman lines provide predictions that have a wide safety margin, so these results are unusual. This phenomenon is seen uniquely in gigacycle fatigue, since conventional 10^7-cycle fatigue strengths show good agreement with the modified Goodman lines [136].

Figure 8 shows typical gigacycle fatigue test results for aluminium alloys. The rotating bending tests at 100 Hz were conducted for three years to reach 10^10 cycles, as well as the ultrasonic fatigue tests at 20 kHz.

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for a week. Although these alloys have been regarded as materials that show no fatigue limit, the A5083P-O alloy clearly shows them. The fatigue limits are in fact obscure when the fatigue tests are terminated at $10^7$ cycles, but they are confirmed by $10^{10}$-cycle fatigue tests. On the other hand, no fatigue limits are observed in A7075-T6 alloy. The presence of the fatigue limits thus depends on the type of aluminium alloy, so further gigacycle fatigue tests are necessary for other types of aluminium alloys to clarify the presence or absence of fatigue limits. Accordingly, A6061-T6 alloy was selected as the next material of the gigacycle fatigue tests, and the results will appear in future in the fatigue data sheets.

3.2. Fatigue properties at high temperatures

The low-cycle fatigue properties at high temperatures were evaluated by employing various strain rates and waveforms. The strain rates range from $10^{-3}$ to $10^{-5}$ s$^{-1}$. The waveforms are shown in Figure 9. Figure 10 shows examples of the results. The effects of the strain rates and the waveforms are more visible at high temperatures. These data are minutely analyzed in technical document No. 11 [137]. In addition to these constant strain amplitude tests, incremental step tests were conducted to clarify cyclic stress-strain curves at high temperatures. Figure 11 shows examples of cyclic stress-strain curves. These data are very practical and useful in designing actual high temperature components.

The high-cycle fatigue properties at high temperatures illustrate whether or not fatigue limits appear. Figure 12 shows an example of the high-cycle fatigue test results. Even if the materials show fatigue limits at room temperature, they frequently disappear at high temperatures. Internal fractures are also observed in these cases. Figure 13 shows an example of the results at intermediate temperatures. In short-life regions, the fatigue strength at intermediate temperatures shows higher fatigue strength than at room temperature because of cyclic strain hardening, whereas it drops in long-life regions because of internal fracturing.

Figure 14 shows an example of long-term strain-controlled fatigue test results at high temperatures, which were used to evaluate high-cycle fatigue properties. In general, high-cycle fatigue properties are evaluated using load-controlled tests, but in these tests, strain amplitude is not always constant. Strain- and load-controlled test results can be combined under the assumption that average strain or stress amplitudes can be used; however, this assumption reduces the reliability of the fatigue design curves. The best way to eliminate dependence on this assumption is to carry out long-
term strain-controlled fatigue tests. This was why the long-term strain-controlled tests were conducted in spite of the considerable time required.

3.3. Fatigue properties of welded joints

The high-cycle fatigue tests for the welded joints were conducted under various conditions to evaluate the effects of specimen size, welding procedures, stress ratios and so on. Figure 15 shows an example of high-cycle fatigue test results employed to evaluate the effects of welding procedures. The mass of data included in the fatigue data sheets is extensive enough to evaluate these effects in detail.

The fatigue data sheets for welded joints uniquely contain the results of crack propagation tests. Figure 16 shows an example of the crack propagation test results. These were conducted using the large sizes of the centre-cracked tension (CCT) specimens, to identify the crack propagation rates for the base metal, the weld metal and the heat-affected zone.

Figure 17 shows an example of long-term high-cycle fatigue test results at 10 Hz up to $10^8$ cycles. The specimens for the welded joints are fatigue-fractured at above $10^7$ cycles, so the presence of fatigue limits is not proven, even by $10^8$-cycle fatigue tests. These results mean that the fatigue design curves for the welded joints should not assume the existence of fatigue limits.

Figure 10. Example of the constant strain amplitude test results at high temperatures. The original images of this figure can be seen in ref [81].
4. Summary

As of the publication of this review paper, the NIMS fatigue data sheets are fully and freely available on the Internet. The fatigue data sheets are temporally only viewed on ‘MatNavi’ (https://smds.nims.go.jp/fatigue/index_en.html) until the middle of 2020, while they will be fully available on a ‘Materials Data Repository (MDR)’ system managed by NIMS after that. Each data sheet can be reached by using DOI listed in references. They comprise a huge database on the fatigue properties of structural materials. The fatigue data have been constantly added to the database for over 40 years. They cover fundamental fatigue properties at room temperature, fatigue properties at high temperatures, and fatigue properties of welded joints. A recent theme of this project is long-term fatigue, which includes so-called gigacycle fatigue. One major advantage of this database is the very small scattering of the data, because the fatigue tests have been conducted at one institution (NIMS).

The fundamental fatigue properties at room temperature were evaluated for steels, aluminium alloys, titanium alloys and so on. High-cycle, low-cycle and gigacycle fatigue properties were then evaluated. The high-cycle fatigue properties determine the fatigue limits, demonstrating that they are chiefly affected by tensile strength and hardness. The low-cycle fatigue properties reveal not only the fatigue lives under cyclic plastic deformation but also cyclic stress-strain curves. The gigacycle fatigue properties were evaluated by three-year fatigue testing at 100 Hz up to $10^{10}$ cycles, as well as by ultrasonic fatigue testing at 20 kHz.

Most of the initial data on fatigue properties at high temperatures is for steels. Low and high-cycle fatigue properties at high temperatures, and fatigue properties of welded joints.
tests were then conducted. The low-cycle fatigue tests at high temperatures were conducted using various strain rates and waveforms, to elucidate their effects. The high-cycle fatigue test results reveal that fatigue limits frequently disappear at high temperatures, in spite of the same materials showing fatigue limits at room temperature. To test long-term fatigue, strain-controlled fatigue tests were conducted up to $10^6$ cycles to evaluate high-cycle fatigue properties under strain-controlled conditions.

The fatigue properties of welded joints were evaluated for steels and aluminium alloys in the form of thick plates. High-cycle fatigue and crack propagation tests were then conducted using large specimens which contained welded parts in as-welded condition. The high-cycle fatigue tests were conducted under various conditions to evaluate the effects of specimen sizes, welding procedures, stress ratios and so on. The crack propagation tests clarified the crack propagation rates for the base metal, the weld metal and the heat-affected zone. For long-term fatigue, high-cycle fatigue tests at 10 Hz were conducted up to $10^8$ cycles, revealing that the presence of fatigue limits is not proven, even in $10^8$-cycle fatigue tests.

The NIMS fatigue data sheets have up to now been used chiefly for industrial purposes. NIMS now intends to promote and extend their use in

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**Figure 14.** Example of the long-term strain-controlled fatigue test results at high temperatures. The original image of this figure can be seen in ref [94].

**Figure 15.** Example of fatigue test results for welded joints to evaluate the effects of welding procedures. The original image of this figure can be seen in ref [106].
Figure 16. Example of crack propagation test results for welded joints. The original image of this figure can be seen in ref [105].

Figure 17. Example of long-term high-cycle fatigue test results for welded joints. The original image of this figure can be seen in ref [126].
academia by improving their accessibility. This review paper is the new gateway for accessing the NIMS fatigue data sheets.

Disclosure statement

No potential conflict of interest was reported by the authors.

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