Effects of surface roughness and notch on fatigue properties for Ti–5Al–2.5Sn ELI alloy at cryogenic temperatures

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Abstract

To evaluate material risk caused by human-error, the effects of surface roughness and notch on the fatigue properties of Ti–5Al–2.5Sn ELI alloy have been investigated at cryogenic temperatures. Specimens with surface roughness changed by emery papers (Grade #600, #100) and notched specimens were prepared ($K_t = 1.5$, 3). The $S$–$N$ curves shifted to higher stress level with a decrease of the test temperature. Regarding the effect of surface roughness, the fatigue strength of the #100-roughness specimens was a little lower than those of the #600-roughness specimens. Fatigue crack initiation sites of each surface roughness specimen at 4 K were found in the specimen interior (internal type fracture). On the other hand, the fatigue strength of the notched specimens was substantially lower than those of the surface roughness specimens. Although fatigue crack initiation sites of the $K_t = 3$ notched specimen were at the notch root (surface type fracture), those of the $K_t = 1.5$ notched specimen were in the specimen interior. The location of the fatigue crack initiation sites changed from the internal type fracture for $K_t = 1.5$ notched specimens to the surface type fracture for $K_t = 3$ notched specimens. Therefore, the $K_t$ values of the internal fatigue crack initiation sites correspond between 1.5 and 3. The root area analysis, which is the size of the crack propagation plane as a shape parameter, the fatigue strength depends on the $\sqrt{\text{area}}$ size (internal fatigue crack initiation site size). Fatigue properties of surface roughness and notched specimens at cryogenic temperatures were expected to be more improved when the grain size of the materials was minimized, i.e. fatigue crack initiation sites were minimized.

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Keywords: Fatigue; Surface roughness; Notch; Ti–5Al–2.5Sn ELI; Internal type fracture; Cryogenic temperatures

1. Introduction

Titanium alloys have high specific strength and many advantageous physical properties, such as low thermal conductivity and high electric resistivity when used as structural materials cryogenic temperatures. They are used as structural materials in equipment utilizing superconductivity, such as superconducting generator and linear motorcar. The Ti–5Al–2.5Sn ELI alloy is also used for inducers of liquid hydrogen fuel turbo pump (FTP) for space rockets. Studies of the launch failure of H-II rocket No. 8 on November 15 in 1999, have revealed fatigue failure, initiating in a flaw 15 $\mu$m in depth and 350 $\mu$m in length that appeared during machining, to have been one of the probable causes [1]. In designing the equipment for the domestically produced H-II rockets for commercial use, therefore, it has become an urgent need to assess the material properties of the materials employed. Acquisition and upgrading of strength data on various materials, including titanium alloys used in H-II rockets, is currently in progress [2].

In particular, it is very important to accumulate fatigue life data on structural materials at cryogenic temperatures to evaluate the long-life reliability and safety of cryogenic machinery. There is not sufficient data on the fatigue properties of titanium alloys at cryogenic temperatures [3–6], and hardly any studies have been carried out on the effect of surface roughness and micro-notches on the fatigue strength of titanium alloys at cryogenic temperatures that take into account factors.

Many investigations have been conducted in the past on the effect of the surface roughness on fatigue strength at room temperature [7]. Since fatigue cracks generally initiate...
on the specimen surface, it is well known that the surface roughness of a specimen has a great effect on its fatigue strength, with a progressively greater effect observed in higher-strength materials. It is also reported that, with respect to the direction of surface roughness, the fatigue strength is more strongly influenced by circumferential direction roughness normal to the stress direction than in the axial direction, that the effect is more marked with greater surface roughness [8], that the surface roughness has a threshold for fatigue strength, and that the surface roughness begins influencing the fatigue strength only when it exceeds this threshold [9]. On the other hand, effects of various kinds of surface finishing including surface notched materials at room temperature have been reported; it has also been reported that hardening by machining has a greater effect on fatigue strength than does surface roughness [10]. The relationship between the notch factor $K_n$ and the stress concentration factor $K_t$ for carbon steels is almost proportional at small $K_t$ values, but gradually shows a plateau with increased $K_t$ values [11]. This tendency is also observed in titanium alloys at cryogenic temperatures. In other words, the fatigue property is lower than predicted by the $K_t$ value [3,6], and the notch sensitivity increases at lower temperature [3]. However, these studies have been carried out using comparatively greater $K_t$ values: little research has been done on the effects of surface roughness and micro-notches of titanium alloys at cryogenic temperatures.

It is therefore the object of this study to clarify the effects of micro-notches attributable to human error, such as surface roughness and flaws sustained during machining, on the fatigue strength of Ti–5Al–2.5Sn ELI alloy at cryogenic temperatures.

2. Experimental procedure

2.1. Material and specimens

The material used in this study was Ti–5Al–2.5Sn ELI alloy. The manufacturing processes for fatigue testing materials are shown in Table 1. The final heat treatment comprised annealing at 973 K for 7.2 ks, followed by cooling in air. The chemical compositions of Ti–5Al–2.5Sn ELI alloy are listed in Table 2. The specimens were cut in perpendicular to the rolling direction. The tensile properties are summarized in Table 3. Five kinds of fatigue test specimens with different surface finishes were used, as shown in Fig. 1. Smooth specimens were ground longitudinally by hand with #600 emery paper. As for the surface-roughness specimens, two kinds of specimens were prepared by circumferentially scratching the area around the minimum diameter of the specimen attached to a lathe for 45 revolutions with #600 and #100 emery papers. They were first polished in the same way as for the smooth specimens, and then scratched. These are hereunder called #600- and #100-roughness specimens, respectively. Surface roughness measurement was then conducted using a scanning laser microscopy (Resolution: 0.01 μm). The measurements showed $R_{max}$ (Maximum roughness) values of 1.07 for the #600-roughness specimen and 10.70 μm for the #100-roughness specimen. As a result of an analysis, the stress concentration factor $K_t$ was provisionally calculated to be 1.18 [1] for the flaw made during machining which was regarded as one of the causes of the accident with the H-II rocket No. 8. It is an interesting question as to what the actual $K_t$ level is. Therefore, notched specimens were prepared in this study to have $K_t = 1.5$ and 3 which are slightly greater than $K_t = 1.18$ by reference to Peterson’s handbook [12].

2.2. High-cycle fatigue test

The testing machine was a servohydraulic model with a dynamic load capacity of ± 50 kN. A sinusoidal cyclic axial load with a stress ratio $R = 0.01$ (minimum load/maximum load) was applied. Fatigue tests were carried out in liquid helium (4 K), in liquid nitrogen (77 K) and at room temperature (293 K). In 4 K tests, a recondensation-type refrigerator [13] was used to keep the liquid helium level constant during the test. To avoid specimen heating as
a result of cyclic loading, the tests at 4 K were carried out at a testing frequency of 4 Hz in the range of fewer than $10^5$-cycles and those over $10^5$-cycles at 10 Hz. The frequency in the 77 and 293 K tests was 10 Hz. To directly assess the effect of low temperatures, the #600-roughness specimens and the notched specimens with $K_t = 1.5$ were tested only at 77 and 4 K. The notched specimens which had survived $10^6$-cycles were further tested under increased load until fracture occurred [14]. Their data were also used because no effects were observed on fatigue properties or the fatigue fracture surfaces.

2.3. Observations of microstructure and fracture surface

The samples for microstructure observations were rough-polished with emery papers, then finished to mirror plane by buffing, and finally chemically etched with Kroll’s etchant. The microstructure was observed by optical microscopy. The fatigue fracture surfaces were also examined using scanning electron microscopy (SEM). X-ray energy dispersion spectroscopy (EDS) was utilized for the chemical analysis of microstructure.

3. Results

3.1. Microstructure

Optical micrograph of Ti–5Al–2.5Sn ELI alloy is shown in Fig. 2. The microstructures of present material consist of α grains with high aspect ratio, with grains elongated in the hot rolling direction. The size of α grains have a minor axis of 5–10 μm and a major axis of 30–90 μm. SEM observation revealed the β-phase at grain boundaries. The composition analysis of the β-phase using EDS revealed that the β-phase were enriched Fe.

3.2. High-cycle fatigue properties of surface roughness specimens

Fig. 3 represents the S–N curves of the smooth specimens and surface roughness specimens at 293, 77 and 4 K. The S–N curves of each specimen shifted to higher stress level or longer life side with a decrease of test temperature, indicating increased fatigue strength. The fatigue strength of the #600- and #100-roughness specimens at 77 and 4 K is slightly lower in the higher stress level or shorter life side region than seen in the smooth specimen. In the lower stress level or longer life side region,

| $T$ (K) | $\sigma_{0.2}$ (MPa) | $\sigma_B$ (MPa) | $\varepsilon$ (%) | $\phi$ (%) |
|---------|---------------------|-----------------|----------------|----------|
| 293     | 800                 | 826             | 14.6           | 48.9     |
| 77      | 1210                | 1254            | 7.2            | 29.4     |
| 4       | 1344                | 1436            | 18.6           | 31.9     |

$T$: temperature; $\sigma_{0.2}$: 0.2% proof stress; $\sigma_B$: ultimate tensile strength; $\varepsilon$: elongation; $\phi$: reduction of area (the number of the tested specimens was 2–3 for each temperature).
However, the degree of decrease in fatigue strength is smaller. The fatigue strength of the #100-roughness specimen at 293 K, on the other hand, is lower than that of the smooth specimen. It was also noted that the rougher the #100-roughness specimen showed lower strength at 77 and 4 K than the #600-roughness specimen.

### 3.3. High-cycle fatigue properties of notched specimens

The S–N curves of the notched specimens with $K_t = 1.5$ and 3 at each test temperature are shown in Fig. 3. The S–N curve of each notched specimen shifted to higher stress level or longer life side with a decrease of test temperature, indicating increased fatigue strength, similar to the smooth specimen and surface roughness specimens. The notched specimens at each test temperature, however, are significantly lower fatigue strength than the smooth specimen and each surface roughness specimen. The specimen with $K_t = 3$ are lower fatigue strength than the specimen with $K_t = 1.5$.

The fatigue strength and fatigue notch factor $K_f$ at $10^6$-cycles at each test temperature are shown in Table 4. Both notched specimens show lower $K_f$ value at lower test temperatures, indicating that the notch sensitivity becomes lower at lower temperatures. Results obtained by Nagai et al. [6] at 4 K for $K_t = 5.7$ shows that the $K_f$ for the fatigue strength at $10^6$-cycles does not exceed 50% of $K_t$ value. For the specimen with $K_t = 3$, the $K_f$ shows its minimum value at 4 K, equivalent to 70% of $K_t$ value. On the other hand, the $K_f$ value has the same magnitude as the $K_t$ value for the specimen with $K_t = 1.5$. This suggests that the notch sensitivity be even greater at $K_t = 1.5$ notched specimen than for $K_t = 3$ notched specimen. Therefore, the relationship between the notch factor $K_f$ and the stress concentration factor $K_t$ for the titanium alloy at cryogenic temperatures is proportional for small values of $K_t$, and gradually shows a plateau with greater $K_t$ values, as seen in carbon steels.

The notch depth of the specimen with $K_t = 1.5$ is about 10 μm, close to the $R_{max}$ of the #100-roughness specimen. However, the fatigue strength of the notched specimen with $K_t = 1.5$ is far lower than that of the #100-roughness specimen with $K_t = 1.5$. The #100-roughness specimen has higher fatigue strength than the single-notched specimen with $K_t = 1.5$ because of a smaller notch effect as a result of the interference effect caused by multiple notches, even when both have the same flaw depth [15].

| Temp. (K) | Fatigue strength (MPa) | Fatigue notch factor ($K_f$) |
|-----------|-------------------------|-----------------------------|
|           | Smooth ($K_t = 1.5$)    | Notched ($K_t = 1.5$)       | Notched ($K_t = 3$) |
| 293       | 355                     | 145                         | 2.45               |
| 77        | 490                     | 240                         | 190                | 2.04 | 2.58 |
| 4         | 515                     | 305                         | 250                | 1.69 | 2.06 |

Fig. 3. S–N curves of Ti–5Al–2.5Sn ELI alloy at 293, 77 and 4 K.
3.4. Location of fatigue crack initiation site

All the fracture surfaces of the fractured specimens were observed by SEM. Many specimens revealed typical internal fatigue crack initiation sites. The results of the observations of the fatigue crack initiation sites are shown in Fig. 3. Open symbols indicate surface type fracture, and closed symbols internal type fracture. The specimens based on the smooth specimens for comparison were surface type fracture at 293 K and internal type fracture at 77 and 4 K. Fatigue crack initiation site of the #600-roughness specimen occurred on the specimen surface only when tested at maximum stress amplitude at 77 K, and the fatigue cracks occurred from the internal specimen for other #600-roughness specimens. For those of the #100-roughness specimen initiated on the specimen surface at 293 and 77 K, and from the internal specimen at 4 K. On the other hand, in the notched specimens it initiated from the internal specimen for \( K_t = 1.5 \) notched specimens, and on the specimen surface for \( K_t = 3 \) notched specimens.

3.5. Internal fatigue crack initiation site

SEM observations of internal fatigue crack initiation sites are not associated with pre-existing defects and inclusions; no clear segregation of any specific elements was observed by EDS analysis.

There have been many reports on internal type fracture in titanium alloys caused without defects and inclusions [16–19]. Previous reports have identified sources such as fine \( \alpha \) phase in \( \alpha \)-type titanium alloy [16], \( \alpha \) phase in \( \alpha + \beta \) type titanium alloy [17,18], and grain boundaries in \( \beta \)-type titanium alloy [19]. Although the internal fatigue crack initiation sites were not identified in this study, the location where stress concentration occurs is generally due to the \( \alpha \) grain boundary in \( \alpha \)-type titanium alloy.

4. Discussion

One potential method of determining whether the presence of surface roughness and notches has any effect on fatigue strength is to identify the location of the fatigue crack initiation sites. Cracks initiated at the bottoms of flaws in the surface roughness specimens, and at the notch roots in the notched specimens. This was also the case for so-called surface type fracture. Since the fatigue crack initiation sites of the smooth specimens used for comparison purposes is internal of the specimen at low temperatures, the effect of flaws and notches on fatigue strength can easily be identified by the location of the fatigue crack initiation sites.

It is known that fatigue strength generally depends on the sizes of defects and inclusions when they cause fatigue fracture. Murakami et al. [20] have evaluated the sizes of the fatigue crack initiation sites, such as non-metallic inclusions, by \( \sqrt{\text{area}} \) (area = the projected area of the fatigue crack initiation site in the maximum principal stress direction), and proposed an equation for the prediction of the fatigue limit using \( \sqrt{\text{area}} \). The sizes of the internal fatigue crack initiation sites observed in this study were calculated by \( \sqrt{\text{area}} \). Effects of the location of fatigue crack initiation and the size of the internal fatigue crack initiation sites on the fatigue strength of the surface roughness specimens and the notched specimens at cryogenic temperatures are discussed below.

4.1. Effect of surface roughness on fatigue strength

The fatigue crack initiation sites of each specimen are located internal specimen or on the surface are indicated in Fig. 3 and are described in 3.3. The #100-roughness specimens at 293 and 77 K indicate surface type fracture. SEM micrographs of the fatigue fracture surface for the #100-roughness specimens tested at 77 K is shown in Fig. 4. Fatigue crack initiates at the bottom of the 10 \( \mu \)m flaw equivalent to \( R_{\max} \) of the #100-roughness specimens. Difference in location of fatigue crack initiation sites between the #600- and #100-roughness specimens is correlated with the fatigue strength of each specimen. In other words, surface type fracture modes have lower fatigue strength in surface roughness specimens.

On the other hand, at 4 K, both surface roughness specimens occurred internal type fracture, as did the smooth
specimens, and therefore the location of the fatigue crack initiation cannot explain their lower fatigue strength. Fig. 5 shows SEM micrographs of the internal fatigue crack initiation sites of the smooth specimen and the #600- and #100-roughness specimens tested at 4 K. In each specimen, the internal fatigue crack initiation sites have elongated shape. Cracks propagated from there and led to final fracture. Detailed SEM observations showed that the internal fatigue crack initiation sites were composed of multiple facets, with the morphology and the size of individual facets similar to those of α grains [6,21].

Fig. 6 shows the relationship between the internal fatigue crack initiation site size (√area) and the number of cycles to failure, (Nf) at each test temperature. A correlation between the √area size and the number of cycles to failure can be observed. In other words, the number of cycles to failure tends to decrease with increased √area size, indicating that the √area size is also an important parameter in the fatigue fracture of titanium alloys. The sizes of the √area for the smooth specimens, the #600- and #100-roughness specimens tested at 4 K are 35–120, 25–125, and 65–225 μm, respectively. Because the √area size of the #600-roughness specimen is in a similar range to that for the smooth specimen, √area size cannot explain the difference in fatigue strength between the two. A slight decrease in fatigue strength, however, does not appear to lead to a great difference in √area size. Nevertheless, the possibility cannot be ruled out that surface flaws in the #600-roughness specimen changed the stress distribution and led to decreased fatigue strength. The same argument holds true for the results of both specimens obtained at 77 K, which show similar √area sizes, with the exception of the #600-roughness specimen which was tested with the stress amplitude 559 MPa and showed fatigue crack initiation sites at the bottom of the flaw. As for the #100-roughness specimens, on the other hand, because the √area sizes are roughly twice those of the smooth specimen and the #600-roughness specimens, the main reason for the lower fatigue strength of the #100-roughness specimens at 4 K could be due to the √area sizes. The effect of the fatigue strength of the √area size is discussed in detail in Section 4.2 below.

4.2. Effect of notches on fatigue strength

The fatigue strength of both notched specimens was substantially lower than that of the smooth specimen and
surface roughness specimens. All the fatigue cracks of the notched specimen with $K_t = 3$ initiated on the notch root at 77 and 4 K. Fig. 7 shows SEM micrograph of fatigue fracture surface of the notched specimen with $K_t = 3$ tested at 4 K. Fatigue cracks initiated from the notch root and propagated from there, and led to final fracture. Therefore, the decrease in fatigue strength of the specimen with $K_t = 3$ is considered to be due to the notch effect.

All the fatigue crack initiation sites of the specimens with $K_t = 1.5$, however, were observed internal specimens, not at the notch root. Fig. 8 shows SEM micrograph of the fatigue fracture surface of the notched specimen with $K_t = 1.5$ tested at 4 K. Fatigue crack initiation sites are composed of multiple facets. Detailed SEM observations of the internal fatigue crack initiation sites indicated, as in smooth specimens, neither pre-existing defects nor inclusions, and EDS analysis revealed no clear segregation of any specific elements. One feature different from those of internal fatigue crack initiation sites in other specimens, however, is that the size is greatly grown much greater. The $\sqrt{\text{area}}$ sizes for the specimen with $K_t = 1.5$ is 290–450 $\mu$m, and the size of some specimens is more than 10 times bigger than that of the smooth specimen with $\sqrt{\text{area}} = 35–120$ $\mu$m. Comparison of the SEM micrographs in Fig. 5 illustrating internal fatigue crack initiation sites in the other specimens and those in Fig. 8 clearly shows a difference in $\sqrt{\text{area}}$ size, since all were taken at the same magnification. Therefore, the significant decrease in the fatigue strength of the specimen with $K_t = 1.5$, notwithstanding the fatigue crack initiation does not initiate on the specimen surface, is considered to be due to the $\sqrt{\text{area}}$ size effect.

Fatigue crack first initiates in the vicinity of the notch root internal the specimen, where the maximum stress occurs. Since the stress amplitude is small, that is, about 50% of the stress amplitude in the smooth specimen, which also showed internal type fracture, crack growth to a certain size is necessary to develop into the main crack. Therefore, several micro-cracks grow and combine during the process of being selected as the main crack [16], leading to the formation of the final facet with the critical $\sqrt{\text{area}}$ size.

The size of the internal fatigue crack initiation sites, $\sqrt{\text{area}}$, is closely related to the fatigue strength in this present alloy as described in the above. Modified S–N curves [14,22] are shown in Fig. 9, where the stress amplitude $\sigma_a$ on the axis of ordinates is normalized by using Murakami’s equation for the prediction of the fatigue limit $\sigma_{w}$ for the specimens which occurred internal type fracture. Murakami’s equation, the fatigue limit $\sigma_{w}$ is represented as follows;

$$\sigma_{w} = \frac{1.56(HV + 120)}{(\sqrt{\text{area}})_N^{16}} \left[ 1 - R \right]^\alpha$$

where $H_v$ (kgf/mm$^2$) is Vickers hardness, $R = \sigma_{min}/\sigma_{max}$ and $\alpha = 0.226 + H_v \times 10^{-4}$. Values of the hardness parameter $H_v$ at the low temperatures were adopted according to a relation between $\sigma_{w}$ and $H_v$ for titanium alloy in the Ref. [23]. When the modified S–N curve is employed, data

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Fig. 7. SEM micrograph of fatigue fracture surface of $K_t = 3$ notched specimen tested at 4 K (stress amplitude = 304 MPa, $N_f = 134,280$).

Fig. 8. SEM micrograph of fatigue fracture surface of $K_t = 1.5$ notched specimen tested at 4 K (stress amplitude = 347 MPa, $N_f = 115,840$).

Fig. 9. Relation of stress amplitude ($\sigma_a$) to predicted fatigue limit $\sigma_{w}$ as a function of number of cycles to failure ($N_f$).
scatter becomes smaller, and the S–N curve is obtained in which $\sigma_f/\sigma_{f_0}$ asymptotically approaches 1, that is, the modified S–N curves show the fatigue limit. No fracture was observed for $\sigma_f/\sigma_{f_0} < 1.0$, indicating that the estimated fatigue limit $\sigma_{f_0}$ was appropriate for the internal type fracture. Therefore, we considered that this analysis is effective for this present alloy. Some data are far from the fitted line. These are considered that the $\sqrt{\text{area}}$ size was overestimated many micro-cracks combined limiting to the critical crack size. Since there are few data of the internal type fracture on the titanium alloys at cryogenic temperatures, it is necessary to conduct a detailed review by additional experiments.

The location of the fatigue crack initiation sites changed from the internal type fracture for $K_t = 1.5$ notched specimens to the surface type fracture for $K_t = 3$ notched specimens. Therefore, the $K_t$ values of the internal fatigue crack initiation sites correspond between 1.5 and 3.

High-cycle fatigue tests of surface roughness specimens and notched specimens of Ti–5Al–2.5Sn ELI alloy at 293, 77, and 4 K show that the fatigue strength of internal type and notched specimens of Ti–5Al–2.5Sn ELI alloy at 293, 77, and 4 K show that the fatigue strength of internal type and notched specimens of Ti–5Al–2.5Sn ELI alloy at cryogenic temperatures, it is necessary to conduct a detailed review by additional experiments. Therefore, the $K_t$ values of the internal fatigue crack initiation sites correspond between 1.5 and 3.

5. Conclusions

Effects of micro-notches attributable to human error, such as surface roughness and flaws sustained during machining, on the fatigue strength of Ti–5Al–2.5Sn ELI alloy were investigated at cryogenic temperatures. The principal results are as follows:

1. In surface roughness specimens, the fatigue strength of the #100-roughness specimens were a little lower than those of the #600-roughness specimens.
2. In notched specimens, the fatigue strength of the $K_t = 3$ notched specimens were lower than those of the $K_t = 1.5$ notched specimens, and those of the notched specimens were substantially lower than those of the surface roughness specimens.
3. Fatigue crack initiation sites of each surface roughness specimen and the $K_t = 1.5$ notched specimens at 4 K occurred in the specimen interior. The root area analysis is applicable for this alloy and showed that the fatigue strength depends on the area size.
4. Although fatigue crack initiation sites of the $K_t = 3$ notched specimens were on the specimen surface (notch root), those of the $K_t = 1.5$ notched specimen were in the specimen interior. The location of the fatigue crack initiation sites showed transition from the internal type fracture for $K_t = 1.5$ notched specimens to the surface type fracture for $K_t = 3$ notched specimens. Therefore, the $K_t$ values of the internal fatigue crack initiation sites correspond between 1.5 and 3.

5. Fatigue properties of surface roughness and notched specimens at cryogenic temperatures were expected to be more improved when the grain size of the materials was minimized, i.e. fatigue crack initiation sites were minimized.

References

[1] Failure Analysis Reports of LE-7 Engine for H-II A Roket (Fracture Surface Analysis), Japanese Rocket Materials Strength Property Data Coordination Committee, NRIM, 2000.
[2] T. Ogata, T. Yuri, Y. Ono, H. Suniyoshi, S. Matsuoka, K. Okita, K. Murakami, Mechanical properties of titanium alloys for FTP of LE-7A at cryogenic temperature, Proceedings of the 23rd International Symposium on Space Technology and Science (selected papers) Jpn. Soc. Aer. Spa. Sci. and Org. Comm. of the 23rd ISTS, Matsue (2002) 658–662.
[3] A.J. Nachtigall, S.J. Klima, J.C. Freche, Fatigue of liquid rocket engine metals at cryogenic temperatures to $-452^\circ$F (67°K), NASA Technical Note, NASA TN D-4274, Lewis Research Center, Ohio, NASA, Washington, DC, December 1967.
[4] Handbook on Materials for Superconducting Machinery, Battele Columbus Lab., Ohio, 1997.
[5] K. Ishikawa, K. Nagai, O. Umezawa, T. Yuri, T. Ogata, Fatigue properties of titanium alloys in liquid helium, JSME Int. J. 34 (1991) 140–143.
[6] K. Nagai, T. Ogata, T. Yuri, K. Ishikawa, T. Nishimura, T. Mizoguchi, Y. Ito, Fatigue fracture of Ti-5Al-2.5Sn ELI alloy at liquid helium temperature, Trans. JSJ 27 (1987) 376–382.
[7] Design Data of Metallic Material Fatigue Strength II Surface Effect, JSME, 1965.
[8] H. Nishitani, R. Inui, Effect of surface roughness of heat-treatment materials for S45C and SCM435 steels on rotary bending fatigue strength, Trans. JSME (A) 49-442 (1983) 693–696 (in Japanese).
[9] E. Siebel, M. Gaier, VHD-Z 98-30 (1956) 1715.
[10] G.M. Sinchair, H.T. Corten, T.J. Dolan, Effect of surface finish on the fatigue strength of titanium alloys RC 130B and Ti 140A, Trans. ASME 79-1 (1957) 89–96.
[11] Fatigue Design Handbook, JSMS, Yokendo Ltd, 1955.
[12] R.E. Peterson, Stress Concentration Design Factors, J. Wiley & Sons, Inc., New York, 1974.
[13] T. Yuri, K. Nagai, T. Ogata, O. Umezawa, K. Ishikawa, Fatigue testing system and results of long-term operation, Cryogenic Eng. 26 (1991) 184–189 (in Japanese).
[14] Y. Murakami, H. Usuki, Prediction of fatigue strength of high-strength steels based on statistical evaluation of inclusion size, Trans. JSME (A) 55-510 (1989) 213–221 (in Japanese).
[15] Y. Murakami, K. Takahashi, T. Yamashita, Quantitative evaluation of the effect of surface roughness on fatigue strength (Effect of depth and pitch of roughness), Trans. JSME (A) 63-612 (1997) 1612–1619 (in Japanese).
[16] O. Umezawa, K. Nagai, K. Ishikawa, Internal crack initiation in high cycle fatigue for Ti–5Al–2.5Sn ELI alloy at cryogenic temperatures, Tetsu-to-Hagane 75 (1989) 159–166 (in Japanese).
[17] O. Umezawa, K. Nagai, K. Ishikawa, Subsurface crack initiation in high cycle fatigue for Ti–6Al–4V alloys at cryogenic temperatures, Tetsu-to-Hagane 76 (1990) 924–931 (in Japanese).
[18] D.F. Neal, P.A. Blenkinsop, Internal fatigue origins in α–β titanium alloys, Acta Metall. 24 (1976) 59–63.

[19] R. Chait, T.S. Desisto, The influence of grain size on the high cycle fatigue crack initiation of a metastable beta Ti alloy, Metall. Trans. 8A (1977) 1017–1020.

[20] Y. Murakami, Quantitative evaluation of effects of defects and non-metallic inclusions on fatigue strength of metals, Tetsu-to-Hagane 75 (1989) 1267–1277 (in Japanese).

[21] Y. Ono, T. Yuri, H. Sumiyoshi, S. Matsuoka, T. Ogata, Effect of alpha grain size on low-temperature fatigue properties of Ti–5%Al–2.5Sn ELI alloy, Miner. Metals Mater. Soc. (2003) 231–237.

[22] Y. Murakami, Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions, Elsevier, 2002.

[23] R. McGee, J. Campbell, R. Carlson, G. Manning, The mechanical properties of certain aircraft structural metals at very low temperatures, Battelle Memorial Inst. WADC-TR-58-386 (1958) 1–57.