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Recent Researches on Gigacycle Fatigue using Ultrasonic Fatigue Testing in NIMS

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Abstract: This paper introduces results of researches on gigacycle fatigue using ultrasonic fatigue testing in NIMS. The first step was investigations of validity of the ultrasonic fatigue testing. As the result, the validity was conformed on conditions where fish-eye fracture occurred. The second step was additional developments on the ultrasonic fatigue testing, such as superimposing mean stress, enlargement of specimens and so on. This step elucidated the mean stress effects and size effects on the fish-eye fracture properties.

Keywords: Gigacycle fatigue, ultrasonic fatigue testing, fish-eye fracture, high-strength steel, Ti-6Al-4V alloy.

1 Introduction

Gigacycle fatigue occurs in high-strength steel. In general, steel materials show a fatigue limit. The fatigue limit is, however, eliminated by fish-eye fracture in high-strength steel [Sakai, Lian, Takeda, Shiozawa, Oguma, Ochi, Nakajima and Nakamura (2010)]. This means that the fish-eye fracture is a key to understand the gigacycle fatigue of high-strength steel. This kind of gigacycle fatigue occurs also in high-strength titanium alloy.

On the other hand, evaluation of the gigacycle fatigue properties is not easy since the gigacycle fatigue tests take long time. For example, a 10^9-cycles fatigue test takes 3 months when the fatigue test is conducted at conventional 100 Hz. Hence, evaluation of gigacycle fatigue properties needs accelerated fatigue testing. For this acceleration, ultrasonic fatigue testing [Mayer (1999); Bathias and Paris (2004)] is a very powerful tool since it achieves 20 kHz and completes the 10^9-cycles in a day. However, frequency effects must sufficiently be investigated before using the ultrasonic fatigue testing. Many researchers had not accepted the ultrasonic fatigue testing for long time because of the extremely high frequency.

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Under these circumstances, NIMS started the research on gigacycle fatigue using the ultrasonic fatigue testing. The first step was investigations of validity of the ultrasonic fatigue testing [Furuya, Matsuoka, Abe and Yamaguchi (2002); Furuya, Abe and Matsuoka (2003); Takeuchi, Furuya, Nagashima and Matsuoka (2008)]. On this step, a key point was frequency effects in case of fish-eye fracture since the gigacycle fatigue is caused by the fish-eye fracture. The second step was additional developments to extend the application of the ultrasonic fatigue testing, such as superimposing mean stress [Furuya and Matsuoka (2005); Takeuchi, Furuya, Nagashima and Matsuoka (2010)], enlargement of specimens [Furuya (2008)] and so on. This paper introduces the results of these researches.

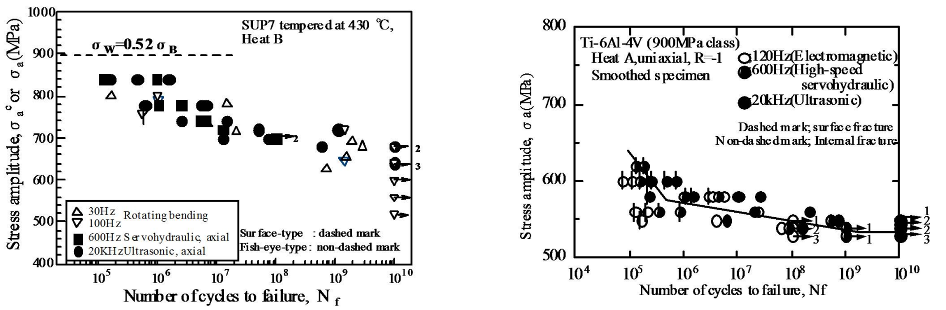
2 Validity of the ultrasonic fatigue testing

The extremely high frequency of 20 kHz is a merit of the ultrasonic fatigue testing, while, at the same time, the fixed frequency is a demerit. The extremely high frequency could cause strain rate effects and affect the fatigue test results. Because of this reason, the ultrasonic fatigue testing had not been used as a practical fatigue test method for long time. However, when NIMS started this research, there was no research that investigated the validity of the ultrasonic fatigue testing on conditions where the fish-eye fracture occurred. Therefore, NIMS investigated the validity focusing on the conditions where the fish-eye fracture occurred.

Figure 1 shows typical ultrasonic fatigue test results, compared with the conventional fatigue test results on conditions where the fish-eye fracture occurs. Figure 2 shows typical fracture surface at around the fish-eye fracture origin. Figure 1 (a) is results of spring steel. In this case, the fatigue tests were conducted at below the conventional fatigue limit, so most of the specimens ended in fish-eye fracture. The origin of the fish-eye fracture is an inclusion as seen in Figure 2 (a). In these results, the ultrasonic fatigue testing shows good agreement with the conventional. Thus, the validity of the ultrasonic fatigue testing is confirmed on conditions where fish-eye fracture occurs in the high-strength steel.

On the other hand, Figure 1 (b) shows results of a Ti-6Al-4V alloy. Also in this case, fish-eye fracture occurred and a fatigue limit was not observed. The difference from the high-strength steel is the fish-eye fracture origin. As seen in Figure 2 (b), the origin was not an inclusion but the matrix itself in case the titanium alloy. In spite of the difference of the fish-eye fracture origin, the ultrasonic fatigue testing shows good agreement with the conventional on conditions where the fish-eye fracture occurs. Hence, regardless of the material, the ultrasonic fatigue testing provides us valid results on conditions where fish-eye fracture occurs.

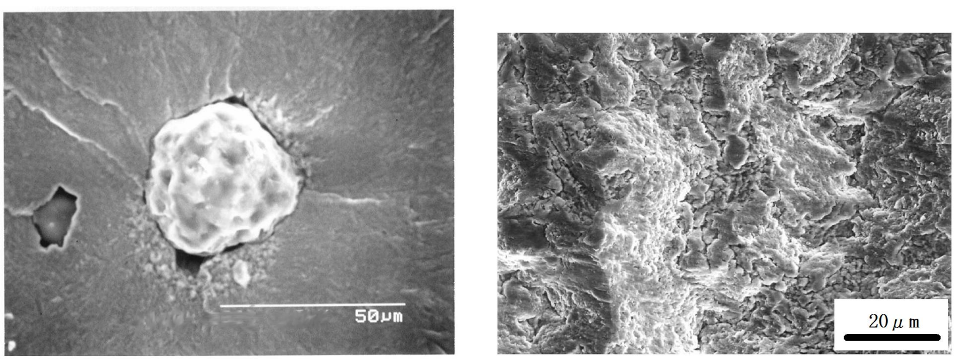
In contrast, the ultrasonic fatigue test results are not always valid in case of conven-



(a) JIS-SUP7 spring steel (b) Ti-6Al-4V alloy

Figure 1: Ultrasonic fatigue test results on conditions where fish-eye fracture occurs

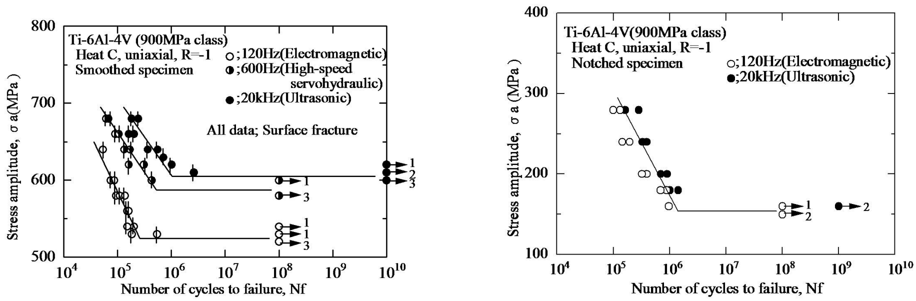
tional surface fracture. Figure 3 shows the results of another heat of the Ti-6Al-4V alloy which is the same grade but shows only surface fracture. In this case, the ultrasonic fatigue testing shows clearly higher fatigue strength as seen in Figure 3 (a). However, the difference is reduced in case of notched specimens as seen in Figure 3 (b). Thus, in case of the surface fracture, the validity of the ultrasonic fatigue testing is likely to depend on the conditions.



(a) JIS-SUP7 spring steel (b) Ti-6Al-4V alloy

Figure 2: Typical fracture surface at around the fish-eye fracture origin

In summary, it is demonstrated that the ultrasonic fatigue testing is applicable at least to the researches on the fish-eye fracture. This means that the usage of the ultrasonic fatigue testing is very limited, while this conclusion is convenient for the researches on the gigacycle fatigue since the fish-eye fracture is a key to understand



(a) Smooth specimens (b) Notched specimens

Figure 3: Ultrasonic fatigue test results in case of surface fracture

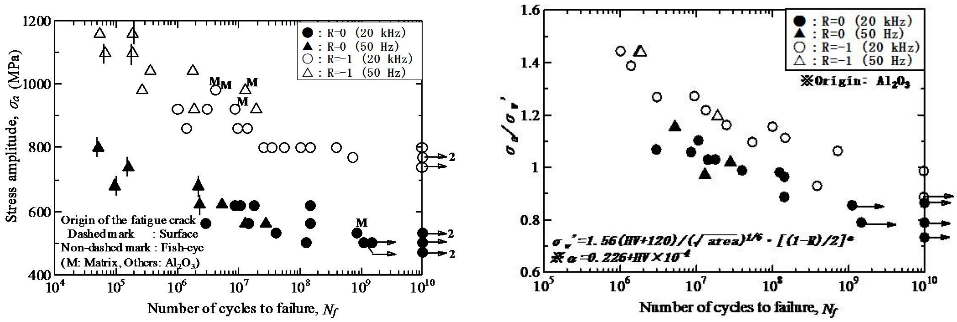
the gigacycle fatigue. Thus, it can be said that the ultrasonic fatigue testing is a powerful tool in the researches on the gigacycle fatigue.

3 Ultrasonic fatigue testing under tensile mean stress

In conventional ultrasonic fatigue testing, the test condition is limited to that of zero mean stress, i.e., fully-reversed condition on which stress ratio is R= -1. This means that the conventional ultrasonic fatigue testing cannot evaluate stress ratio effects in spite of their importance in designing mechanical components. To solve this problem, the ultrasonic fatigue testing system has been embedded in a load frame of a tensile tester. In this system, a static load can be applied during the ultrasonic fatigue testing. Although this method had already been reported in literatures [Mayer (1999); Bathias and Paris (2004)], application to researches on the fish-eye fracture was not so many.

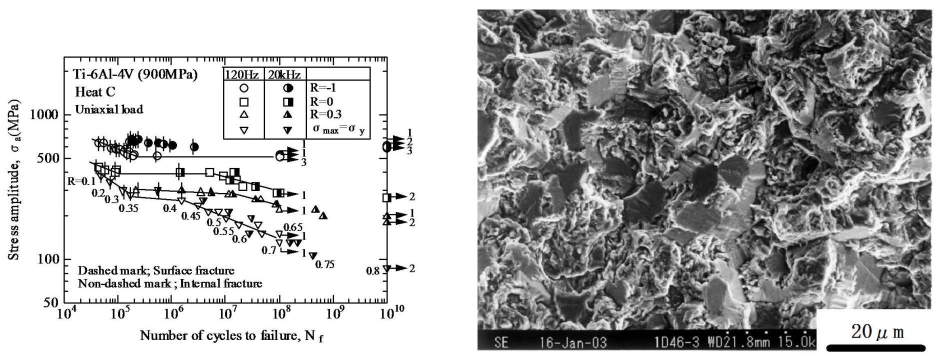
Figure 4 shows fatigue test results for high-strength steel. In the conventional $S-N$ diagram, results of the ultrasonic fatigue testing are continuously connected with those of the conventional even under a R= 0 condition. In the modified $S-N$ diagram, in which only results of fish-eye fracture are plotted and stress amplitudes are normalized by each fatigue limit calculated by Murakami's equation [Murakami (2002)], it is more clearly confirmed that the ultrasonic fatigue testing shows good agreement with the conventional. Hence, even by using this system, valid results are obtained on conditions where fish-eye fracture occurs.

Figure 5 shows fatigue test results for the Ti-6Al-4V alloy. Although this alloy shows only surface fracture on a R= -1 condition as seen in Figure 3 (a), fish-eye fracture occurs under tensile mean stress conditions and the ultrasonic fatigue test-



(a) Conventional $S-N$ diagram (b) Modified $S-N$ diagram

Figure 4: Ultrasonic fatigue test results for high-strength steel under tensile mean stress

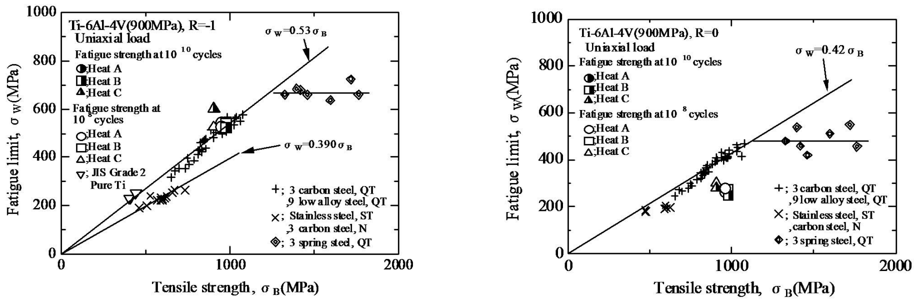


(a) $S-N$ diagram (b) Typical fracture surface

Figure 5: Ultrasonic fatigue test results for Ti-6Al-4V alloy under tensile mean stress

ing shows good agreement with the conventional in case of the fish-eye fracture. This means that the Ti-6Al-4V alloy is more prone to the fish-eye fracture on the tensile mean stress conditions than on the zero mean stress condition, and the ultrasonic fatigue testing is applicable to evaluate the mean stress effects on the fish-eye fracture properties. On the tensile mean stress conditions, the fish-eye fracture origin revealed a cluster of facets as seen in Figure 5 (b), and the facet sizes were very close to the α-grain sizes.

Figure 6 show comparison of fatigue strength between the Ti-6Al-4V alloys and steels. On the R = -1 condition, the Ti-6Al-4V alloys show as high fatigue strength as the tempered-martensite steels, while the fatigue strength is lower than that of the tempered-martensite steels on the R = 0 condition. This means that the mean stress effects are very large on the Ti-6Al-4V alloys. Figure 7 shows an endurance limit diagram of the Ti-6Al-4V alloys, compared with a modified Goodman line. Because of the large mean stress effects, the Ti-6Al-4V alloys show lower fatigue strength than the modified Goodman line at around R = 0. In general, the modified Goodman line is expected to provide us a safe-side prediction, so the trend seen in Figure 7 is very dangerous.



(a) On a $R = -1$ condition (b) On a $R = 0$ condition

Figure 6: Fatigue strength of Ti-6Al-4V alloys compared with steels

In summary, the ultrasonic fatigue testing system with a load frame successfully evaluates the mean stress effects on the fish-eye fracture properties. The mean stress effects on the fish-eye fracture are not always similar to those on the surface fracture as seen in the Ti-6Al-4V alloys. Therefore, it is very important to elucidate the mean stress effects on the fish-eye fracture properties by using this system.

4 Enlargement of the ultrasonic fatigue test specimens

In fatigue tests, specimen size is an important factor, i.e., the larger the better. However, the ultrasonic fatigue test specimens used in our tests were relatively small. Moreover, our past research had suggested that size effects could be significant in the case of the fish-eye fractures [Furuya, Abe and Matsuoka (2003)]. These were motivations of this development. In enlarging the specimen size, a straight section was adopted at the minimum diameter section, as well as using a larger diameter. Introducing the straight section effectively enlarges the risk volume [Murakami (2002)], which is a measure of the size of the region subject to high stress in fatigue test specimens.

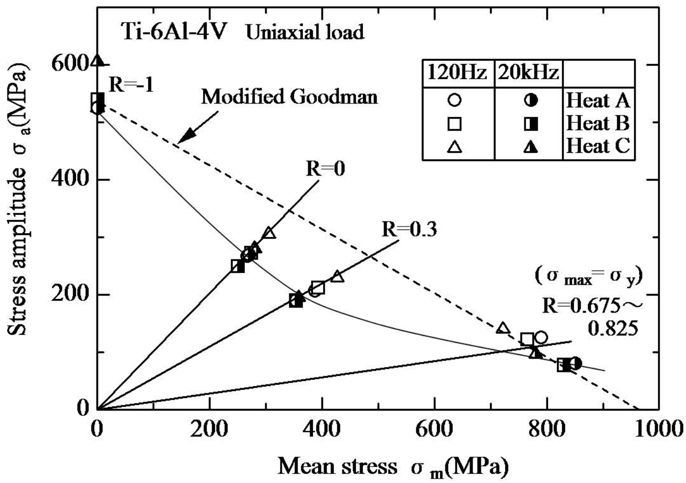
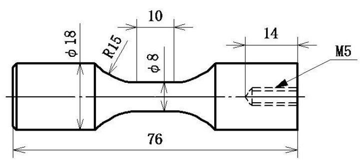
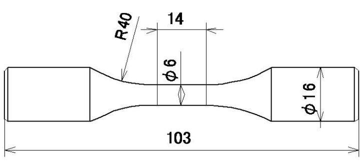


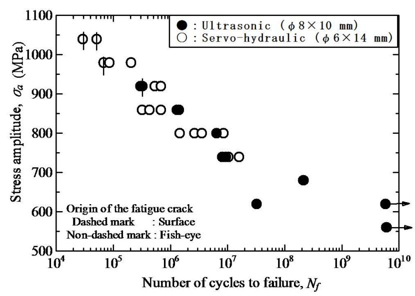
Figure 7: Endurance limit diagram of Ti-6Al-4V alloys



(a) Ultrasonic fatigue test specimen



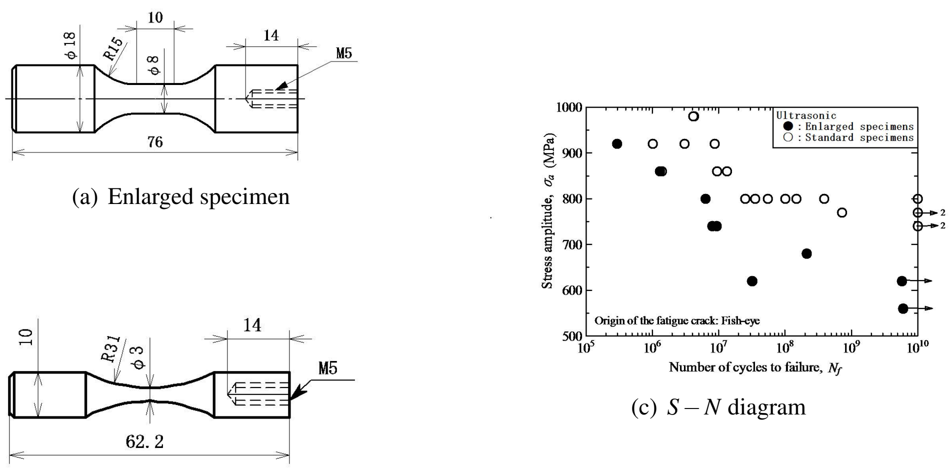
(b) Servo-hydraulic fatigue test specimen



(c) $S-N$ diagram

Figure 8: Fatigue test results using the enlarged specimens

Figure 8 shows the ultrasonic fatigue test results for high-strength steel using the enlarged specimens, compared with the conventional fatigue test results. The risk volume of the ultrasonic fatigue test specimens is almost equal to that in the conventional, so the comparison in Figure 8 is fair. As the result, the ultrasonic fatigue testing shows good agreement with the conventional on conditions where the fish-eye fracture occurs. This result supports the validity of ultrasonic fatigue testing using enlarged specimens. Figure 9 shows the ultrasonic fatigue test results for high-strength steel using two sizes of specimens. As seen in this figure, the enlarged specimens show much lower fatigue strength than our standard small specimens. Namely, large size effects are observed on conditions where the fish-eye fracture occurs in high-strength steel. Figure 10 shows inclusion sizes at the fish-eye fracture origin, plotted on a Gumbel probability paper. The inclusion sizes at the fish-eye fracture origin are also larger in the enlarged specimens. This means that the size effects are caused by difference of the inclusion sizes appearing at the fish-eye fracture origin.



(a) Enlarged specimen

(b) Our standard specimen

(c) $S-N$ diagram

Figure 9: Ultrasonic fatigue test results using two sizes of specimens

Thorough this research, it is found that the specimen sizes are much more important in fish-eye fracture than in conventional surface fracture. The large size effect strongly urges the use of large specimens when conducting gigacycle fatigue tests on high-strength steel. In other words, using small specimens is very dangerous, since they are likely to show misleadingly high gigacycle fatigue strength.

5 Conclusion

This paper introduced our results of researches on gigacycle fatigue using the ultrasonic fatigue testing. The researches consisted of two steps: (1) investigations of

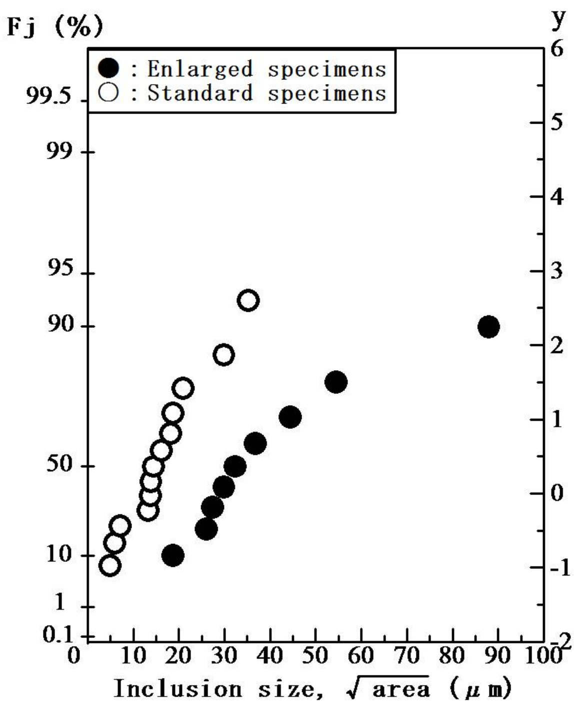


Figure 10: Inclusion sizes at the fish-eye fracture origin

validity of the ultrasonic fatigue testing, and (2) additional developments to extend the application of the ultrasonic fatigue testing, such as superimposing mean stress, enlargement of specimens and so on. The main conclusions of these researches are as follows.

1. Ultrasonic fatigue testing showed good agreements with conventional fatigue testing on condition where fish-eye fracture occurred regardless of the materials. Hence, it is applicable to the researches on gigacycle fatigue caused by the fish-eye fracture.

2. The ultrasonic fatigue testing system superimposing mean stress successfully evaluated the mean stress effects on the fish-eye fracture. This system elucidated notable mean stress effects on gigacycle fatigue properties of Ti-6Al-4V alloys.

3. The enlarged ultrasonic fatigue test specimens produced valid results and elucidated large size effects on fish-eye fracture of high-strength steel. This

result urges the use of large specimens in conducting gigacycle fatigue tests on high-strength steel.

References

Bathias, C.; Paris, P. C. (2004): *Gigacycle Fatigue in Mechanical Practice*. Marcel Dekker.

Furuya, Y.; Matsuoka, S.; Abe, T.; Yamaguchi, K. (2002): Gigacycle fatigue properties for high-strength low-alloy steel at 100 Hz, 600 Hz and 20 kHz. *Sctipta Materialia,* vol. 46, pp. 157–162.

Furuya, Y.; Abe, T.; Matsuoka, S. (2003): 10^{10}-cycle fatigue properties of 1800 MPa-class spring steel. *Fatigue Fract. Eng. Mater. Struct.,* vol. 26, pp. 641–645.

Furuya, Y.; Matsuoka, S. (2005): Ultrasonic fatigue properties of high-strength steel under tensile mean stress. *Trans. JSME Ser. A,* vol. 71, pp. 1201–1206.

Furuya, Y. (2008): Specimen size effects on gigacycle fatigue properties of high-strength steel under ultrasonic fatigue testing. *Sctipta Materialia,* vol. 58, pp. 1014–1017.

Mayer, H. (1999): Fatigue crack growth and threshold measurements at very high frequencies. *Int. Mater. Rev.,* Vol. 44, pp. 1–34.

Murakami, Y. (2002): *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions*. Elsevier.

Sakai, T.; Lian, B.; Takeda, M.; Shiozawa, K.; Oguma, N.; Ochi, Y.; Nakajima M. and Nakamura, T. (2010): Statistical duplex $S-N$ characteristics of high carbon chromium bearing steel in rotating bending in very high cycle regime. *Int. J. Fatigue*, Vol. 32, pp. 497-504.

Takeuchi, E.; Furuya, Y.; Nagashima, N.; Matsuoka, S. (2008): The effect of frequency on the giga-cycle fatigue properties of a Ti-6Al-4V alloy. *Fatigue Fract. Eng. Mater. Struct.,* vol. 31, pp. 599–605.

Takeuchi, E.; Furuya, Y.; Nagashima, N.; Matsuoka, S. (2010): Effect of stress ratio on giga-cycle fatigue properties for Ti-6Al-4V alloy. *Tetsu-to-Hagane,* vol. 96, pp. 36–41.