Effect of Stress Ratio and Notch on Fatigue Strength of Commercial Pure Titanium

Toshiaki IWATA

National Institute of Maritime, Port and Aviation Technology

6-38-1, Shinkawa, Mitaka, Tokyo, 181-0004, JAPAN; TEL: +81-422-41-3752; FAX: +81-422-41-3112; E-mail: iwata@m.mpat.go.jp

Abstract

Titanium alloys such as Ti-6Al-4V are widely used in the aerospace domain worldwide; consequently, they have been extensively investigated, and the accumulated data has facilitated their use in the construction of structural members. In contrast, commercial pure (CP) Ti, which is cheaper than Ti alloys is widely used in the general industry, especially in the marine domain in Japan because it exhibits superior seawater corrosion resistance and biocompatibility. However, CP titanium has a strong anisotropy and consists of an hcp crystal structure; therefore, the strength data are insufficient owing to its short use history as a structural material, and some of its mechanical material properties remain unclear. Herein, the effect of mean stress and stress concentration on the fatigue strength of CP Grade 2 titanium was evaluated for the application range expansion of CP titanium. The results indicated that the fatigue limit in the longitudinal direction was 80–84% that in the transverse direction for smooth specimens. However, no significant difference was noted in the fatigue limit in both the directions for notched specimens. Furthermore, it was noted that it is necessary to apply at least S_a-0.5S_u line to design the safe side in CP Grade 2 titanium.

1. Introduction

Titanium alloys such as Ti-6Al-4V are widely used in the aerospace domain worldwide; consequently, they have been extensively investigated, and the accumulated data has facilitated their use in the construction of structural members.[1–3] In contrast, commercial pure (CP) Ti, which is cheaper than Ti alloys is widely used in the general industry, especially in the marine domain in Japan because it exhibits superior seawater corrosion resistance and biocompatibility.

CP titanium is suitable for marine material. It has begun to be used for not only the structural members of fishing-boat and yacht but also the non-structural members including the equipment of a ship product of the severe corrosion environment such as the exhaust pipe or the seawater condenser, from about 2000. To support the fatigue design because there was no established code of the fatigue design for titanium welded structure including the titanium alloys, author studied the fatigue strength evaluation of the principal welded joints which constitutes titanium hull structure[4]. However, the data of fatigue strength of CP titanium as the parent material of welded structure is insufficient unlike ship's structural materials such as steel and aluminum alloys. In this study, the effect of mean stress and stress concentration on the fatigue strength of CP Grade 2 titanium was evaluated for the application range expansion of CP titanium.

2. Material and experiments

2.1 Test material

According to the Japanese Industrial Standard JIS-H-4600[5], a hot rolling plate made of CP Grade 2 titanium, TP340H, was used as the test material. The chemical composition of the test material listed in the inspection certification is summarized in Table 1. [6] The microstructure and the crystal orientation distribution, observed using the electron backscatter pattern system of a field emission type scanning electron microscope are shown in Fig. 1. [6] The figure indicates no difference in the crack propagation life because a clear difference doesn't exists in both the particle size distribution and the crystal orientation distribution between the longitudinal (L) direction specimen section (LT-ST side) and the transverse (T) direction specimen section (L-ST side).

The mechanical properties of the test material obtained by performing a tensile test on the JIS-Z-2201 (ISO-6892MOD) [7] No. 5 specimen are listed in Table 2. [6] The value listed in the inspection certification and the standard value of TP340H as per JIS-H-4600 are presented in Table 2. In addition, the mechanical properties of mild steel according to the rules pertaining to the survey and construction of steel ships[8] are

Table 1 Chemical composition (wt%). [6]

	N	C	H	Fe	O	Ti
Inspection Certification	0.00	0.00	0.001	0.04	0.10	Bal.

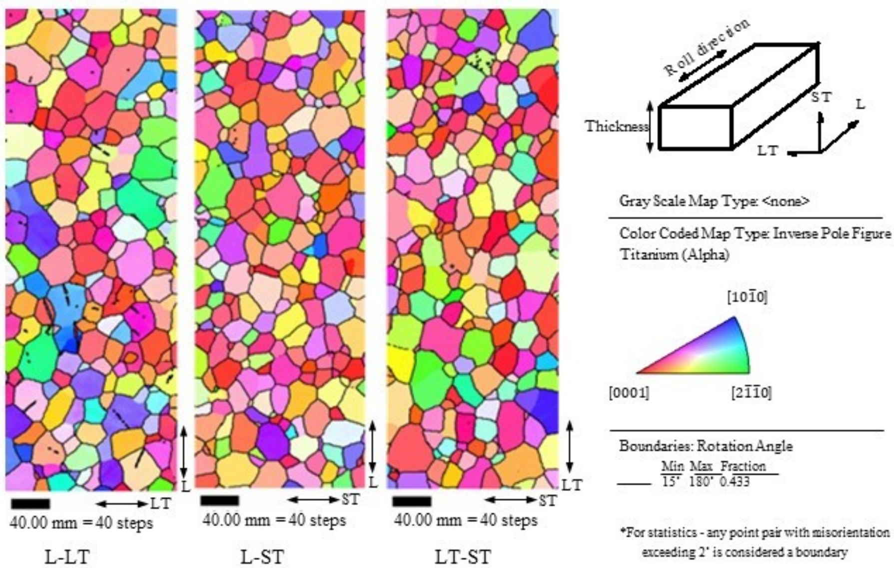

Fig. 1 Microstructure and crystal orientation distribution. [6]

Table 2 Mechanical properties. [6]

	Direction	Modulus of longitudinal elastisity	Proportional limit stress	0.2% Proof stress	Maximum tensile stress	Fracture stress	True fracture stress	Yield ratio	Uniform elongation	Total elongation	Contraction of area
		E	S_e	$S_{0.2}$	S_u	S_f	S_t	$S_{0.2}/S_u$	d_u	d_f	F
		GPa	MPa						%		
JIS H4600 TP340 H				≥215	340-510					≥23	
Inspection Certification	Transverse			342	446					37	
Exp. $_{Ave}$	Longitudinal	106	123	248	400	311	675	0.619	13.9	41.9	54.0
	Transverse	118	201	337	415	287	748	0.812	7.36	45.7	61.7

2.2 Test specimens

The configuration of the smooth test specimens is shown in Fig. 2 [6] and that of the notched test specimens is shown in Fig. 3. [6] The fatigue test specimens were sampled in the L-direction or T-direction from the test material along with the JIS-Z-2201 (ISO-6892MOD) No. 5 specimen. In this study, the stress concentration factor of the notched test specimens was assigned three different values (K_t = 2.0, 2.93, 3.77) to simulate the notch in the form of a weld toe or other types of shapes of the ship structure. The parallel part including the notch and R part were smoothed by using emery paper 800#.

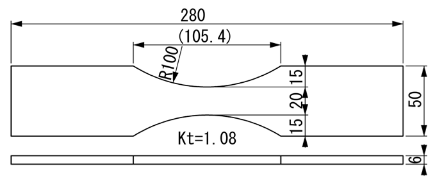

Fig. 2 Configuration of smooth test specimen. [6]

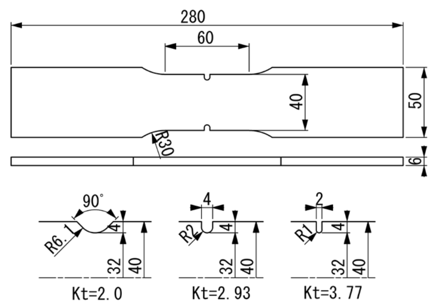

Fig. 3 Configuration of notched test specimens. [6]

2.3 Test conditions

The fatigue tests were performed under load control of the sine wave in a hydraulic servo controlled fatigue test machine. For a plate specimen, the cycling frequency was set to 1–5 Hz to avoid buckling in the case of compression. The stress ratio in the fatigue test was assigned three values (R = -1, 0, 0.3) for smooth specimens and one value (R = 0) for notched specimens.

3. Results

The relation between the nominal stress range *"Delta"S* and number of cycles to failure *N* is shown in Fig. 4 [6] for each stress ratio and Fig. 5 [6] for each notch shape. The slope *n* and parameter *C* of the *S–N* curve were determined using the least-squares method. The solid lines indicate the 50% survival probability lines. The dotted lines indicate the 97.5% survival probability lines calculated by subtracting the double standard deviations of log N from the solid lines.

As shown in Table 2, [6] although the difference between the maximum tensile stress (S_u) for the L-direction and T-direction is only approximately 4%, the 0.2% proof stress for the L-direction is approximately 74% that for the T-direction.

As shown in Fig. 5, [6] the fatigue limit for the L-direction was 80–84% that for the T-direction for smooth specimens. In addition, the fatigue strength for the L-direction was lower than that for the T-direction in the finite life region, which is the inclined region in the *S*–*N* curve, for notched specimens. However, no significant difference was noted in the fatigue limit for both directions for notched specimens.

The maximum stress of the notch root (stress concentration factor K_t × fatigue limit S_w) is presented in Table 3. [6] In all the notched specimens, K_tS_w in the L-direction was larger than $S_{0.2}$ for $K_t \geq 2$; in contrast, K_tS_w in the T-direction was smaller than $S_{0.2}$ for $K_t \leq 2.93$. In other words, the crack in the L-direction was initiated owing to the stress in the plastic region, such as for steel materials; in contrast, the crack in the T-direction was mainly initiated owing to the stress in the elastic region. Therefore, because the crack in the T-direction, initiated owing to the stress of the elastic region was affected by the plastic region of the L-direction, it is considered that the fatigue limits for the L-direction and T-direction did not have a significant difference for notched specimens.

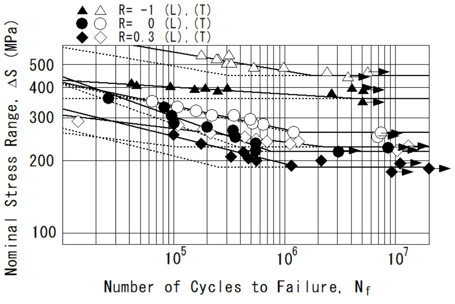

Fig. 4 Relation between nominal stress range and number of cycles to failure for different stress ratios. [6]

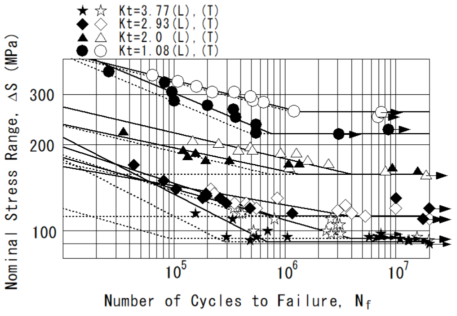

Fig. 5 Relation between nominal stress range and number of cycles to failure for different notch shapes. [6]

Table 3 Maximum stress of notch root (MPa). [6]

Direction	0.2% Proof	(Maximum stress of notch root)

	stress	/ (0.2% Proof stress)			
	$S_{0.2}$	$K_tS_w/S_{0.2}$			
		K_t=1	K_t=2	K_t=2.93	K_t=3.77
Longitudinal	248	0.95	1.27	1.33	1.39
Transverse	337	0.84	0.93	0.97	1.05

4. **Discussion**

4.1 Effect evaluation of mean stress

Considering the fatigue limit obtained from the fatigue test, the endurance limit diagrams for the L-direction and T-direction are shown in Figs. 6 and 7, respectively. The vertical and horizontal axes respectively denote the nominal stress amplitude S_a and mean stress S_m. In general, in the case of steel materials, the experimental results are approximate to the S_a–S_t diagram for $S_m \leq S_{0.2}$; therefore, the modified Goodman diagram corresponds to the design of the safe side [9]. In contrast, in the case of CP titanium, for both the directions, as shown in Fig. 6 [6] and Fig. 7, [6] the experimental results for R=0 and 0.3 were approximate to the Soderberg diagram and modified Goodman diagram, respectively. Therefore, the modified Goodman diagram did not correspond to the design of the safe side. In other words, CP titanium is considerably more influenced by the mean stress than steel materials are, and the fatigue limit decreased in a range between the Soderberg diagram and the modified Goodman diagram with increase in the mean stress. Both the Goodman diagram defined by 1/3 S_u and the S_a-0.5S_u line defined by 1/2 S_u are shown in addition to the modified Goodman diagram defined by S_u in Fig. 6 [6] and Fig. 7. [6]

The relations between the fatigue limit S_w and the maximum tensile stress S_u or the 0.2% proof stress $S_{0.2}$ are presented in Table 4. [6] Takeuchi et al. [1] reported the relations between S_w and S_u for the case of surface fractures in carbon steel, low alloy steel, and aluminum alloy. Although these relations have not been established for CP titanium, a similar relation can be established with R = 0 when $S_{0.2}$ is used in place of S_u. In other words, in the case of CP Grade 2 titanium, the fatigue strength is affected more by the 0.2% proof stress than by the maximum tensile stress. This tendency is different from that of steel materials and the Ti-6Al-4V alloy. Therefore, it can be considered that the test results were located in the range between the Soderberg diagram and the modified Goodman diagram, for both the L-direction and T-direction, as shown in Fig. 6 [6] and Fig. 7. [6] In particular, for R = 0, the test results were nearly equivalent (L-direction) or slightly smaller (T-direction) compared to the Soderberg diagram defined by $S_{0.2}$. Therefore, it is necessary to apply at least a S_a-0.5S_u line to design the safe side in CP Grade 2 titanium.

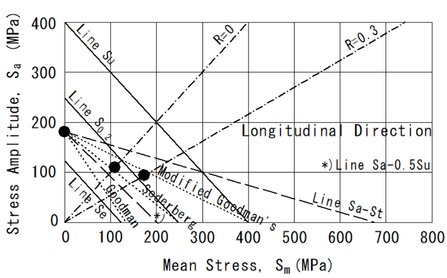

Fig. 6 Endurance limit diagrams (Longitudinal direction). [6]

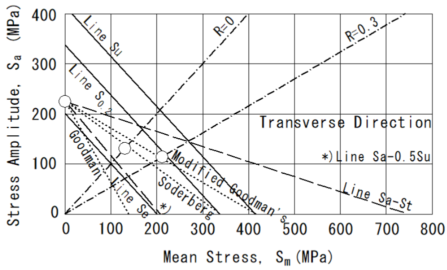

Fig. 7 Endurance limit diagrams (Transverse direction). [6]

Table 4 Relation between fatigue limit and tensile stress or 0.2% proof stress. [1, 6]

		Stress Ratio	
		R=-1	R=0
Carbon steel, Low alloy steel, Aluminum alloy[1)]		S_w=0.53S_u	S_w=0.42S_u
CP Titanium	Longitudinal	S_w=0.45S_u	S_w=0.27S_u
		S_w=0.73$S_{0.2}$	S_w=0.44$S_{0.2}$
	Transverse	S_w=0.54S_u	S_w=0.31S_u
		S_w=0.67$S_{0.2}$	S_w=0.39$S_{0.2}$

4.2 Effect evaluation of stress concentration

The relation between the stress concentration factor K_t and fatigue notch factor K_f is shown in Fig. 8. [6, 9~12] Generally, in the case of steel materials and aluminum alloy, K_f is nearly equal to K_t for $K_t \leq 2$; it is gradually saturated as K_t approaches 4. Its value is equal to approximately 2, 2.5, and more than 2.5 in the cases of aluminum 6061-T6; [10] aluminum 5083-H112 [10] and medium carbon steel except C = 0.5%; [11] and aluminum 5083-O [10] or 6005C-T5 [13] and medium carbon steel C = 0.5%, [11, 12] respectively. In the case of CP titanium, K_f in the L-direction is nearly equal to that of aluminum 5083-H112 and medium carbon steel except C = 0.5%. In the T-direction, K_f is nearly equivalent to that of aluminum 5083-O or 6005C-T5 and medium carbon steel C = 0.5%.

Based on the result of tension and compression fatigue tests for R = -1 performed using CP Grade 1 titanium hot rolling stick JIS-H-4650[14] TB270H, Takao et al. reported [15] that no non-propagation crack occurs because the resistance of crack generation is larger than that of crack propagation. Therefore, a crack propagates until fracture if a crack is generated once, even though the notch sensitivity of CP titanium is lower than that of carbon steel.

The relation between the stress concentration factor K_t and fatigue limit S_w is shown in Fig. 9. [6] The limit of crack propagation is generated at approximately K_t = 3 in the case of steel; therefore, the limit lines of both the crack generation and crack propagation can be observed in the crack generation limit diagram. In contrast, in the case of CP titanium, the entire crack propagated until fracture in the evaluated range $K_t \leq$ 3.77. Therefore, Region II was not observed between Regions I and III. Here, Region II is the region in which the non-propagation crack is generated but does not propagate until fracture. In particular, in the L-direction, the limit of crack generation (solid line) at approximately K_t = 2 is larger than 30% the value of $K_f = K_t$ line (dotted line). This tendency is different from that of steel for which the limit of crack generation around K_t = 2 is almost equal with that of the $K_f = K_t$ line. This aspect indicates that the fatigue strength does not decrease to the numerical value calculated geometrically using the stress concentration factor K_t, and the fatigue strength at approximately K_t = 2 is insensitive to the notch because the resistance of crack generation is large. In contrast, the value of S_w in K_t = 3.77 decreases by 20% compared to the value of S_w in K_t = 2.93, and the value of S_w cannot be considered to be saturated and reaching the limit. This aspect indicates that the fatigue strength continues decreasing even in the range beyond K_t = 3. It is considered that the fatigue strength at approximately K_t = 3.77 is sensitive to the notch because the non-propagating crack is not generated.

The relation between the stress concentration factor K_t and notch sensitivity factor *"eta"* is shown in Fig. 10. [6, 16] As shown in Fig. 10, [6, 16] at approximately K_t = 2, the notch sensitivity factor of CP Grade 2 titanium in the T-direction is larger than that of carbon steel, and the corresponding factor in the L-direction is smaller than that of carbon steel. In contrast, at K_t = 3.77, the notch sensitivity factor in the L-direction is nearly equivalent to that of S15C [16] (ISO C15) or S35C [16] (ISO C35), and in the T-direction, the corresponding value is nearly equivalent to that of S45C [16] (ISO C45). The non-propagating crack, which is generated at approximately K_t = 2 in carbon steel was not observed in CP Grade 2 titanium.

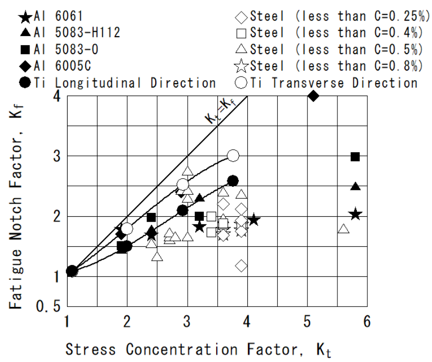

Fig. 8 Relation between stress concentration factor K_t and fatigue notch factor K_f. [6, 9–12]

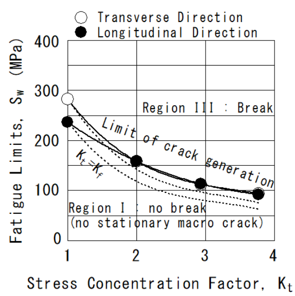

Fig. 9 Crack generation limit diagram. [6]

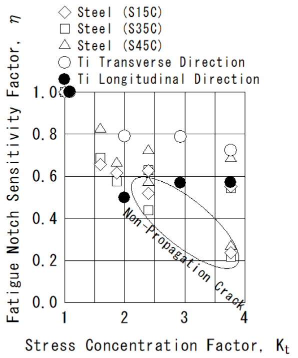

Fig. 10 Relation between stress concentration factor, K_t, and notch sensitivity factor, *"eta"*. [6, 16]

4.3 Endurance limit diagrams of notched specimens

The endurance limit diagrams of the notched specimens, for both L-direction and T-direction are shown in Fig. 11 [6] and Fig. 12 [6], respectively. Following the design method of fatigue strength suggested in the case of steel, [17] in this study, S_w/K_f at K_t = 3.77 where K_t is maximum was adopted for the y-intercept of the vertical axis (i.e., L-direction: $S_w/K_{f2.581}$, T-direction: $S_w/K_{f3.006}$). Furthermore, the true fracture stress S_t is suggested for the x-intercept of the horizontal axis in the case of steel for which the experimental results of the smooth specimens are approximate to the S_a-S_t diagram for $S_m \leq S_{0.2}$. [9] However, the experimental results of the smooth specimens in the case of CP titanium were approximate to the Soderberg diagram or slightly smaller than it. Therefore, both lines for which $S_{0.2}$ or 0.5S_u was adopted for the x-intercept of the horizontal axis were shown in these figures. It is necessary to adopt a value of less than 0.5S_n for the x-intercept of the horizontal axis because adopting $S_{0.2}$ for it cannot help predict the safe side.

In the recommendations for fatigue design of welded joints by the International Institute of Welding (IIW), [18] the two million cycle fatigue strength of a butt welded joint without a grinding weld toe in R = 0 is 90 MPa in the case of steel materials. This value of 90 MPa (i.e., R = 0, S_m = 45 MPa, S_a = 45 MPa) is shown in Fig. 11 [6] and Fig. 12. [6] As shown in these figures, the intersection of the R = 0 line on the S_w/K_f-0.5S_u line of CP Grade 2 titanium corresponds to a larger value than the abovementioned 90 MPa. Therefore, in the design of the welding structure composed by CP Grade 2 titanium, which has a mechanical strength most similar to that of ship classification mild steel, it appears that the design fatigue strength of the steel welding structure is applicable.

The intersection of the endurance limit line (the limit line of crack generation) to the curve at which the 0.2% proof stress $S_{0.2}$ is divided by the stress concentration factor K_t is located near the boundary point of the limit lines of both crack generation and crack propagation. [17] Therefore, the $S_{0.2}/K_{t3.77}$ line was also shown in these endurance limit diagrams as the limit line of the non-propagation crack generation. In the case of steel materials in which the non-propagation crack is generated, the y-intercept S_w/K_f of the vertical axis is considerably larger than that of the $S_{0.2}/K_{t3.77}$ line. That is to say, the endurance limit line (the limit line of crack generation) S_w/K_f-S_t generally intersects the $S_{0.2}/K_{t3.77}$ line in the region in which the value of S_m is larger than that of the $R = 0$ line. In contrast, in the case of CP titanium, the fatigue notch factor K_f in K_t = 3.77 is large, as shown in Fig. 8, and the fatigue strength continues to decrease even in the range beyond K_t = 3.0, as shown in Fig. 9. Therefore, in the case of CP titanium, the intersection of the S_w/K_f-0.5S_u line to $S_{0.2}/K_{t3.77}$ line shifts to the direction in which the value of S_m reduces in comparison to that of steel materials. Furthermore, these two lines do not intersect when $R \geq 0$ because the value of S_m on the intersection is smaller than the R = 0 line. Therefore, in the case of CP titanium, it is considered that there is no region in $R \geq 0$ in which the crack does not propagate until fracture even though the non-propagation crack is generated.

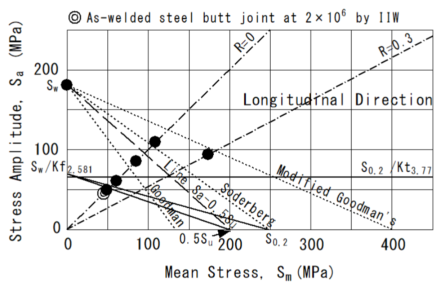

Fig. 11 Endurance limit diagrams (Longitudinal direction). [6]

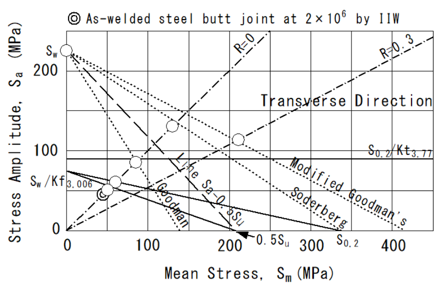

Fig. 12 Endurance limit diagrams (Transverse direction). [6]

5. Conclusions

The following conclusions could be derived:

The fatigue limit for the L-direction was 80–84% that for the T-direction for smooth specimens. However, no significant difference was noted in the fatigue limit for both directions for notched specimens.

The test results were located in the range between the Soderberg diagram and the modified Goodman diagram, for both the L-direction and T-direction. It is necessary to apply at least a S_a-0.5S_u line to design the safe side in CP Grade 2 titanium.

At a stress concentration factor K_t of approximately 2, the notch sensitivity factor of CP Grade 2 titanium in the T-direction was larger than that of carbon steel, and the corresponding value in the L-direction was smaller than that of carbon steel. In contrast, for K_t = 3.77, its value in the L-direction is nearly equivalent to that of S15C (ISO C15) or S35C (ISO C35), and in the T-direction, its value is nearly equivalent to that of S45C (ISO C45). The non-propagation crack, which is generated at approximately K_t = 2 in carbon steel was not observed in CP Grade 2 titanium.

In the design of the welding structure composed by CP Grade 2 titanium, which has a mechanical strength that is most similar to that of the ship classification mild steel, it appears that the design fatigue strength of the steel welding structure is applicable for use.

6. Acknowledgement

This study was carried out in cooperative research with The Japan Titanium Society. The author cordially thanks Dr. Y. Kobayashi, former staff of the National Maritime Research Institute, for his assistance in planning this research. I would like to thank Editage (www.editage.com) for English language editing. The source file of this document is an article published in Journal of the society of material science, Japan 66 (2017) 913–920. The text of this document is a translation from the original article in Japanese.

7. **References**

[1] Y. Furuya and E. Takeuchi, Mater. Sci. Eng. A, 598(2014) 135-140.

[2] K. Hayashi, S. Nishida and N. Hattori, Trans. Jap. Soc. Mech. Eng. (A). 65 (1999) 2080–2085. [In Jap.]

[3] D. B. Lanning, T. Nicholas and G. K. Haritos, Int. J. Fatigue, 27(2005) 45-57.

[4] T. Iwata and K. Matsuoka, Welding in the World, 48 (2004) 40–47.

[5] JIS-H-4600:2007. Titanium and titanium alloys –Sheets, plates and strips; Japanese Industrial Standards: Tokyo, 2010

[6] T. Iwata, J. Soc. Mater. Sci. Jap. 66 (2017) 913–920. [In Jap.]

[7] JIS-Z-2201:1998(ISO-6892MOD). Test pieces for tensile test for metallic materials; Japanese Industrial Standards: Tokyo, 2010

[8] Kyokai, N. K. (Class NK), Rules and Guidance for the Survey and Construction of Steel Ships, Part K Materials, Nippon Kaiji Kyokai (Class NK): Tokyo, 2019.

[9] R. I. Stephens, A. Fatemi, R. R. Stephens and H. O. Fuchs, “Metal Fatigue in Eng. 2nd ed.” 76–77, Wiley-Interscience, New York, 2000.

[10] K. Takeuchi and E. Tanaka, Sumitomo light metal technical reports, technical data sheet 9–4 (1968) 15–17. [In Jap.]

[11] F. Korber and u. M. Hempel, Mitt. KWI Eisenforschung 21 (1939) 1–19.

[12] Ed. Jap. Soc. Mech. Eng., “Design document of the metal materials fatigue strength I”, (1982) 141–142, Jap. Soc. Mech. Eng. [In Jap.]

[13] K. Takeuchi, J. light metal welding & construction, 33 (1995) 556–565. [In Jap.]

[14] JIS-H-4650:2007. Titanium and titanium alloys –Rods and bars; Japanese Industrial Standards: Tokyo, 2010

[15] K. Takao and H. Nishitani, Proc. of the 2nd Intern. Conference on Fatigue and Fatigue Thresholds, 827–834, 1984.

[16] N. -A. Noda, H. Nishitani, S. Harada and Y. Takase, Int. J. Fatigue, 17(1995) 237-244.

[17] R. I. Stephens, A. Fatemi, R. R. Stephens and H. O. Fuchs, “Metal Fatigue in Eng. 2nd ed.” 200–206, Wiley-Interscience, New York, 2000.

[18] A. F. Hobbacher, “Recommendations for Fatigue Design of Welded Joints and Components 2nd ed.”, 47, Springer, Switzerland, 2016.