Weld World (2013) 57:235–241
DOI 10.1007/s40194-012-0018-y

RESEARCH PAPER

Effect of preload and stress ratio on fatigue strength of welded joints improved by ultrasonic impact treatment

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Received: 8 December 2011 / Accepted: 11 July 2012 / Published online: 15 December 2012

Abstract
Introduction Ultrasonic impact treatment (UIT) is a post-weld technique to be used for improving the fatigue strength of welded joints. The technique makes use of ultrasonic vibration to impact and plastically deform the weld toe, consequently creating beneficial compressive residual stress near the treated area. Since the compressive residual stress is considered to be a main reason for the improvement of fatigue strength, the improvement effect may be influenced by preload and stress ratio. In the case of ship structures, welded parts may be locally subjected to a stress near the yield strength of the material in heavy weather, and mean stress may change significantly depending on the loading conditions.
Tests In the present paper, fatigue tests were conducted using transverse non-load carrying fillet welds to identify the condition that UIT provides substantial benefit for fatigue strength of welded joints. The material used is AH36 shipbuilding high-strength steel. In the investigation of the preload effect, tensile stress of 90 % or compressive stress of 60 % of the yield strength of the base metal is applied prior to fatigue tests, where the stresses are defined as nominal stress.
Results It is found that UIT is more effective than grinding on fatigue strength improvement of welded joints even after application of the preload. The effect of stress ratio was investigated by fatigue tests at stress ratios of 0.1, 0.5, and −1. Though the fatigue strength of the UIT-treated weld joint decreased as the stress ratio increased, the fatigue limits of the UIT-treated weld joint is fairly higher than that of as-welded joints even at the stress ratio of 0.5. Finally, fatigue tests were conducted under random sequence of clustered loading, which may simulate wave-induced load histories. UIT provides substantial benefit for fatigue strength of welded joints under actual service loading in ship structures.

Keywords (IIW Thesaurus) Ultrasonic processing · Fatigue improvement · Welded joints · Residual stresses · Structures

1 Introduction

Ultrasonic impact treatment (UIT) has attracted much attention due to its effectiveness in fatigue strength improvement of welded joints for steel structures. This technique makes use of ultrasonic vibration to impact and plastically deform

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Doc. IIW-2319, recommended for publication by Commission XIII "Fatigue of Welded Components and Structures".

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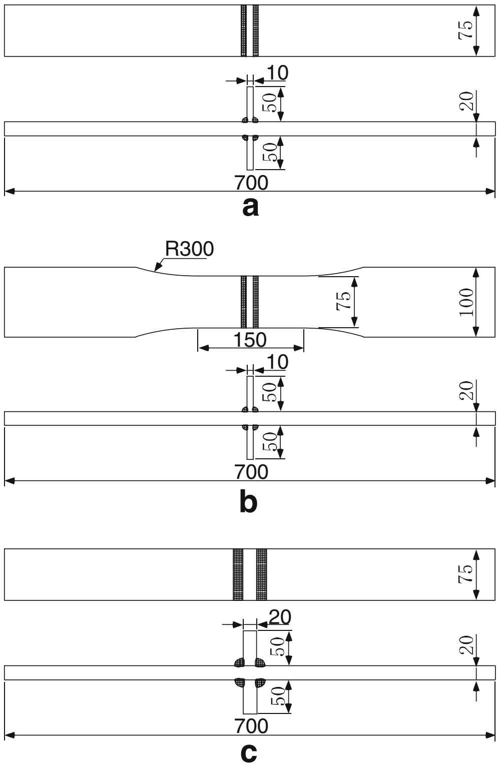

Fig. 1 Geometries of specimens: **a** as-welded, **b** UIT, **c** grinding

Table 1 Chemical composition of AH36

Thickness [mm]	Element [wt%]					
	C	Si	Mn	P	S	Nb
10	0.15	0.20	1.13	0.014	0.003	0.01
20	0.15	0.22	1.12	0.014	0.005	0.01

Table 2 Mechanical properties of AH36

Thickness [mm]	Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Charpy absorbed energy at 0 °C [J]
10	417	518	25	193
20	392	520	20	251

Table 3 Chemical composition of SF-1

Element [wt %]				
C	Si	Mn	P	S
0.06	0.50	1.40	0.015	0.010

Table 4 Mechanical properties of SF-1

Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]	Charpy absorbed energy at 0 °C [J]
520	580	30	91

the weld toe, consequently creating beneficial compressive residual stress near the treated area. Fatigue performance of welded joints is significantly improved mainly by the compressive residual stress. Besides, UIT has an advantage in treatment speed so that it can reduce the operating time compared to using other methods such as grinding, hammer peening, and needle peening. Also, vibration and noise are considerably smaller than the other methods. The beneficial effects of UIT for fatigue performance of welded joints have been demonstrated in previous studies [1–10].

However, the fatigue strength of welded joints improved by UIT is supposed to be influenced by overload and stress ratio [11–15]. The overload may cause redistribution of residual stress due to local plastic deformation at the stress concentration area. Since the compressive residual stress decreases the local stress ratio near the treated weld toe so as to enhance its fatigue strength, the effect of the compressive residual stress may be reduced at the condition of high stress ratio. In the case of ship structures, welded parts may be locally subjected to a stress near the yield strength of the material in heavy weather, and mean stress may change significantly depending on the loading conditions. Therefore, in order to design ship structures, it is especially important to evaluate the effect of the overload and the stress ratio. In the present study, fatigue tests using transverse non-load carrying fillet welds were conducted under various test conditions to identify the condition that UIT provide substantial benefit for fatigue strength of the welded joints.

2 Test specimen

The geometries of specimens are shown in Fig. 1. The material used is AH36 shipbuilding high-strength steel, whose chemical composition and mechanical properties are shown in Tables 1 and 2, respectively. The specimens were welded by the flux-cored arc welding (FCAW) with SF-1 that corresponds to JIS Z 3313 T49J0T1-1CA-UH5. The chemical composition and mechanical properties of SF-

Table 5 Welding parameters

Diameter of wire [mm]	Welding speed [mm/min]	Welding current [A]	Welding voltage [V]
1.2	340	300	28–29

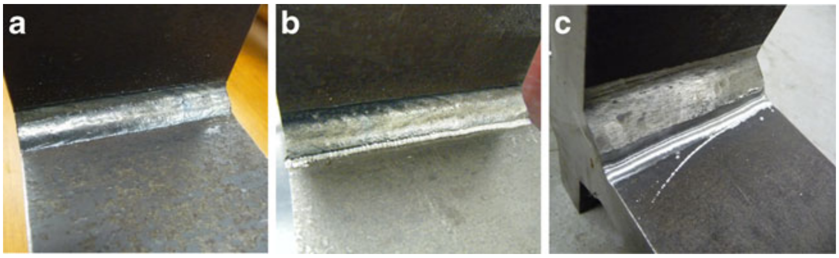

Fig. 2 Weld shape of specimens: **a** as-welded, **b** UIT, **c** grinding

1 are shown in Tables 3 and 4, respectively. The welding parameters are given in Table 5. The weld joints for as-welded and UIT are fabricated by one pass welding with leg length of 8 mm. The weld joints for grinding are fabricated by three passes welding with a leg length of 15 mm.

The UIT equipment used for this study is Esonix™ 27 UIS. The operating frequency of the ultrasonic generator was 27 kHz, the indenter used was 3-mm-diameter pins. The weld toes of the specimens were treated until the original weld toe lines disappear.

On the grinding, firstly, entire weld beads were treated by the disc grinder, then the weld toes were smoothly rounded using a burr grinder with a 10-mm-diameter tool. The weld shape of the as-welded and treated specimens is shown in Fig. 2.

3 Fatigue tests and residual stress measurements of welded joints with and without preload

In order to simulate the influence of the overload on the stability of compressive residual stresses induced by UIT, some of the fatigue tests were performed after preloading the specimens. The preload is: (a) tensile stress of 90 % of the yield strength of the base metal, which is equal to 353 MPa or (b) compressive stress of 60 % of the yield strength of the base metal, which is equal to 235 MPa. The stresses were defined as nominal stress. The compressive stress was determined in terms of preventing buckling of the specimen.

3.1 Residual stress measurement

The X-ray diffraction ($\sin^2\psi$ [16, 17]) method was employed for the residual stress measurement. An X-ray stress analyzer "XSTRESS 3000" was used with a standard collimator of 3-mm-spot size. The peak location of diffraction was calculated using the half-breadth method and five ψ angles were used to determine the slope of d vs. $\sin^2\psi$ plot. The measurements were conducted along the line illustrated in Fig. 3. The direction of the measured residual stresses was transverse to the weld bead (i.e. parallel to the x-axis).

Results of the residual stress measurement are shown in Fig. 4. Before preload, compressive residual stress of 350~400 MPa was measured near the UIT line. This compressive residual stress was decreased to 220~300 MPa after preload. Relatively high compressive residual stress was remained even after application of the preloads.

3.2 Results of fatigue tests

The results of fatigue tests are shown in Fig. 5 and Table 6. Fatigue strength at 2×10^6cycles and fatigue strength increase of each welded joint are summarised in Table 7.

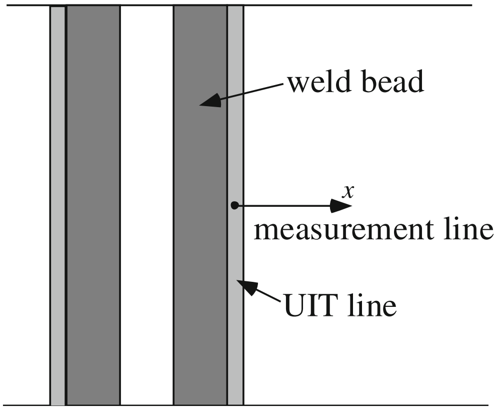

Fig. 3 Measurement line

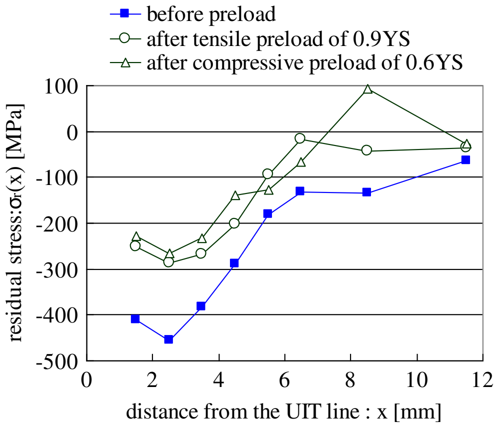

Fig. 4 Results of residual stress measurement

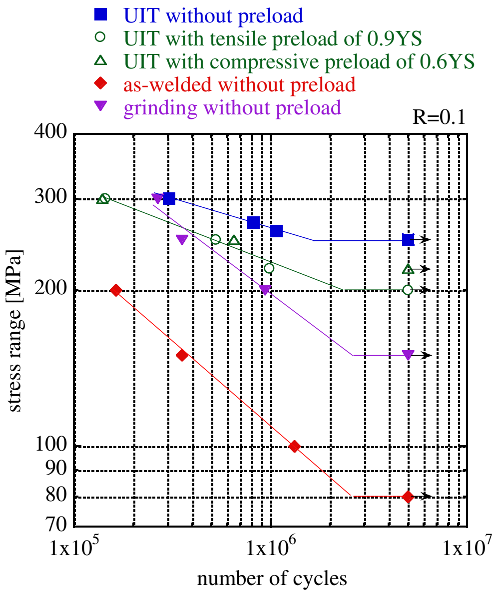

Fig. 5 *S–N* plots for fatigue tests with and without preload

The fatigue strength of the welded joints was significantly improved by UIT. After application of preloads, the fatigue strength of UIT-treated welded joint was slightly decreased. The effects of the tensile and the compressive preloads were approximately the same. Even after application of the preloads, the fatigue strength at 2×10^6cycles and the fatigue strength increase of UIT-treated specimen was greater than that of ground specimen. However, from the *S–N* plots in Fig. 5, the high benefit of UIT is limited on high number of cycles (e.g. on lower stress ranges) in comparison to grinding. The beneficial effect of compressive residual stress is reduced on higher stress ranges. Additionally, it should be noted that the scatterband of the test results was not considered due to limited number of test specimens.

Table 6 Results of fatigue tests with and without preload

Weld toe condition	Preload	Fatigue life [$\times10^6$]	Stress range [MPa]	Stress ratio
As-welded	–	0.164	200	0.1
As-welded	–	0.354	150	0.1
As-welded	–	1.32	100	0.1
As-welded	–	>5.0	80	0.1
UIT	–	>5.0	250	0.1
UIT	–	0.818	270	0.1
UIT	–	1.067	260	0.1
UIT	–	0.304	300	0.1
UIT	Tension[a]	>5.0	200	0.1
UIT	Tension[a]	0.144	300	0.1
UIT	Tension[a]	0.525	250	0.1
UIT	Tension[a]	0.983	220	0.1
UIT	Compression[b]	0.139	300	0.1
UIT	Compression[b]	0.65	250	0.1
UIT	Compression[b]	>5.0	220	0.1
UIT	Compression[b]	>5.0	200	0.1
Ground	–	0.353	250	0.1
Ground	–	>5.0	150	0.1
Ground	–	0.934	200	0.1
Ground	–	0.266	300	0.1

[a] Tensile preload of 0.9 YS

[b] Compressive preload of 0.6 YS

Table 7 Fatigue strength at 2×10^6cycles and fatigue strength increase of each welded joint

	Fatigue strength at 2×10^6cycles [MPa]	Fatigue strength increase [%]
As-welded	87	–
UIT	243	179
UIT+preload	206	137
Grinding	157	80

4 Fatigue tests under several conditions of stress ratio

In order to investigate the effect of stress ratio on fatigue strength of welded joints improved by UIT, fatigue tests were carried out at stress ratio (R) of 0.1, 0.5, and −1.

The *S–N* plots for the fatigue tests are compared in Fig. 6. The results of fatigue tests at R=0.5,−1 are shown in Table 8. The relation between the stress ratio and the fatigue strength at 2×10^6cycles is shown in Fig. 7 and Table 9, respectively. Although the fatigue strength of the UIT treated weld joint

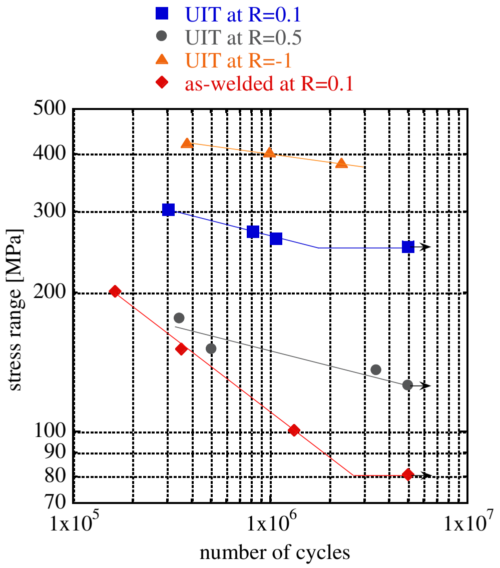

Fig. 6 *S–N* plots for fatigue tests under several conditions of stress ratio

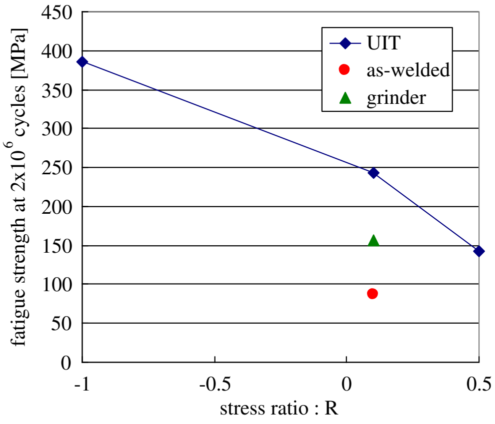

Fig. 7 Relation between the stress ratio and the fatigue strength at 2×10^6 cycles

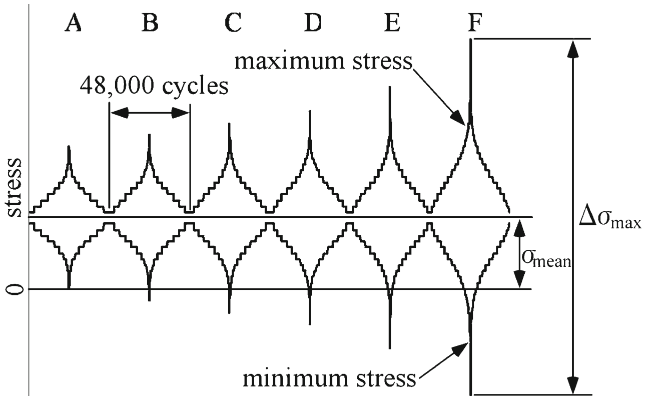

Fig. 8 Load patterns of the storms

Table 8 Results of fatigue tests at R=0.5,−1

Weld toe condition	Fatigue life [$\times 10^6$]	Stress range [MPa]	Stress ratio
UIT	0.346	175	0.5
UIT	0.503	150	0.5
UIT	>5.0	125	0.5
UIT	3.45	135	0.5
UIT	0.378	420	−1
UIT	0.99	400	−1
UIT	2.295	380	−1

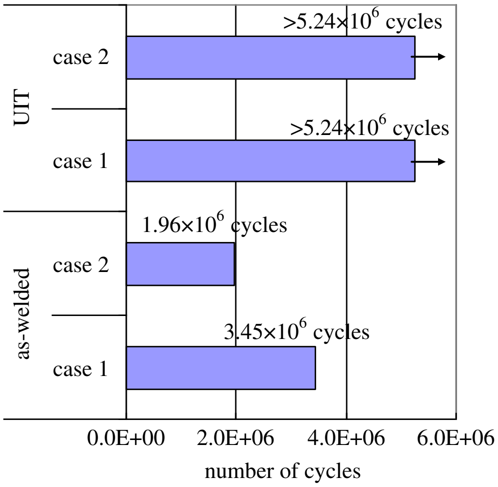

Fig. 9 Results of fatigue tests under simulated wave-induced load histories

Table 9 Fatigue strength at 2×10^6 cycles at each stress ratio

Stress ratio	Fatigue strength at 2×10^6 cycles [MPa]
0.1	243
0.5	142
−1	386

Table 10 Number of occurrence of the storms

Storm	A	B	C	D	E	F
Number of occurrence in 20 years	42	25	12	7	6	1

decreased with the increase of the stress ratio, the fatigue limit of the UIT treated weld joint is fairly higher than that of as-welded joints even at $R=0.5$. It is also confirmed that UIT is sufficiently beneficial under reversed cyclic loading ($R=-1$).

5 Fatigue tests under simulated wave-induced load histories

In order to verify the fatigue performance of welded joints improved by UIT under actual load histories of ship structures, fatigue tests under simulated wave-induced load histories are carried out using a storm model [18]. The main points of the storm model are as follows:

- The distribution function of long-term wave-induced load is described by an exponential distribution.
- The time history of wave condition is divided into two types; "calm sea condition" and "storm condition". The calm sea condition is not considered on the fatigue tests because fatigue damage would be negligibly small under this condition.
- Load histories under the storm condition are described by six clustered load patterns A, B, C, D, E, and F are defined as illustrated in Fig. 8. Each clustered load sequence consists of 48,000 loading cycles and the number of occurrence in a 20-years ship life is defined in Table 10.

In the present study, two load cases were defined as below:

Case 1: $\Delta\sigma_{\max}=400$ MPa, $\sigma_{\mathrm{mean}}=100$ MPa
Case 2: $\Delta\sigma_{\max}=500$ MPa, $\sigma_{\mathrm{mean}}=100$ MPa,

Where stress range of 50 MPa or less was omitted from the load cycles for reduction of testing time. In case 2, the maximum stress applied in storm F becomes 350 MPa, thus it is supposed to be significantly severe loading condition for the welded joints. Storm F was applied first and the following storms were applied by random sequences so that the redistribution of residual stress arises at the beginning of the experiments. The compressive residual stress introduced by UIT decreases with the application of storm F as predicted from Fig. 4. The UIT treated and as-welded specimens were tested under each load case. One sample was used for each series.

The results of the fatigue tests are shown in Fig. 9. Fatigue cracks were not observed in UIT treated welded joints for both load cases until 5.24×10^6 load cycles, which is corresponding to 40 years of storm loads. In contrast, as-welded joints were failed at 3.45×10^6cycles and 1.96×10^6cycles for cases 1 and 2, respectively.

6 Conclusions

Effect of preload and stress ratio of fatigue strength of welded joints improved by UIT is experimentally investigated considering that UIT is applied to ship structures. The conclusions of this study are summarised as follows:

- The fatigue strength of UIT-treated welded joint was slightly decreased after application of preload due to redistribution of compressive residual stress. However, the benefit of UIT was significantly greater than that of grinding even after application of the preload, where tensile stress of 90 % or compressive stress of 60 % of the yield strength of the base metal is applied as preload.
- Although the fatigue strength of the UIT-treated weld joint decreased with increasing the stress ratio, the fatigue limits of the UIT-treated weld joint was fairly higher than that of as-welded joints even at the stress ratio of 0.5. UIT is also beneficial under reversed cyclic loading.
- The fatigue performance of UIT treated welded joints was significantly higher than that of as-welded joints under simulated wave-induced load histories. The benefit of UIT could be expected in ship structures under actual load histories.
- It should be noted that the uncertainty of the results are still remained due to limited number of test specimens under constant and variable loading. An investigation on the scatterband of the test results should be conducted in the future work.

References

1. Statnikov ES, Trufyakov VI, Mikheev PP, Kudryavtsev Yu F (1996) Specification for weld toe improvement by ultrasonic impact treatment, IIW Doc. XIII-1346-96
2. Statnikov ES (1997) Comparison of post weld deformation methods for increase in fatigue strength of welded joints, IIW Doc. XIII-1668-97
3. Haagensen P, Statnikov ES Lopez-Martinez L (1998) Introductory fatigue tests on welded joints in high strength steel and aluminium improved by various methods including ultrasonic impact treatment (UIT), IIW Doc. XIII-1748-98
4. Statnikov ES (2000) Applications of operational ultrasonic impact treatment (UIT) technologies in production of welded joints, IIW Doc. XIII-1667-97. Weld World 44(3):11–21
5. Roy S, Fisher JW, Yen BT (2003) Fatigue resistance of welded details enhanced by ultrasonic impact treatment (UIT). Int J Fatig 25:1239–1247
6. Lihavainen VM, Marquis G, Statnikov ES (2004) Fatigue strength of a longitudinal attachment improved by ultrasonic impact treatment, IIW Doc. XIII-1990-03. Weld World 48:67–73, Nos. 5–6
7. Tominaga T, Matsuoka K, Sato Y, Suzuki T (2007) Fatigue improvement of weld repaired crane runway girder by ultrasonic impact treatment, IIW Doc. XIII-2170-07
8. Nose T (2008) Ultrasonic peening method for fatigue strength improvement. J Jpn Weld Soc 77(3):210–213, in Japanese

9. Pedersen MM, Mouritsen OO, Hansen MR, Andersen JG, Wenderby J (2009) Conparison of post weld treatment of high strength steel welded joints in medium cycle fatigue, IIW Doc. XIII-2272-09
10. Maddox SJ, Dore MJ, Smith SD (2010) Investigation of ultrasonic peening for upgrading a welded steel structure, IIW Doc. XIII-2326-10
11. Lixing H, Dongpo D, Yufeng Z (2005) Investigation of the fatigue behavior of the welded joints treated by TIG dressing and ultrasonic peening under variable-amplitude load. Int J Fatig 27:95–101
12. Marquis G, Bjork T (2008) Variable amplitude fatigue strength of improved HSS welds, IIW Doc. XIII-2224-08
13. Wang T, Wang D, Huo L, Zhang Y (2009) Discussion on fatigue design of welded joints enhanced by ultrasonic peening treatment (UPT). Int J Fatig 31:644–650
14. Mori T, Shimanuki H, Tanaka M (2011) Effect of UIT on fatigue strength of web-gusset welded joints considering service condition of steel structures, IIW Doc. XIII-2376-11
15. Tai M, Miki C (2011) Improvement effect of fatigue strength by peening treatment under variable amplitude loadings, IIW Doc. XIII-2378-11
16. Macherauch E, Mueller P (1961) The $\sin^2\psi$ method for x-ray stress determination. Z Angew Phys 13:305–312, in German
17. JSMS (2002) Committee on x-ray study on mechanical behavior of materials. (in Japanese)
18. Tomita Y, Hashimoto K, Osawa N, Terai K, Wang Y (2002) Study on fatigue design load for ships based on crack growth analysis, ASTM STP, n 1439, Fatigue Testing and Analysis under Variable Loading Conditions: 420–434