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Prediction of fatigue life distribution of marine propeller materials †

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Abstract

Engineering materials have been studied and developed for a remarkably long time, but there are few reports about marine propeller materials. Recently, some researchers have studied the material strength of marine propellers. However, studies on parametric sensitivity and probabilistic distribution of fatigue life of propeller materials have not yet been carried out. In this study, we have evaluated strength characteristics of AlBC3 and HBsC1, both of which have been used for marine propellers using air jet chisel. Then a method to predict the probabilistic distributions of fatigue life of propeller materials is presented and the influence of several parameters on the life distribution is discussed.

Keywords: Marine propeller; Parametric sensitivity; Probabilistic method; AlBC3; HBsC1; Air jet chisel, Monte Carlo simulation

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1. Introduction

The propeller is one of the most critical elements in propelling ships. Damage to propellers is most commonly caused by large deformation, fatigue fracture and erosion. These types of damage generally occur when the ship is in service. Accidents caused by propeller damage are remarkably dangerous. Although this demands that designers pay more attention to preventing propeller damage, research about marine propellers is lacking. Moreover, research about the fatigue life of propeller materials is needed.

There is some related research studying the marine propeller, such as the effect of corrosion pit repairing method on the strength of marine propeller[1], analysis of the structural failure of marine propeller blades[2], a study on the fatigue strength of highly skewed propeller[3], etc.

The research grafting fracture mechanics and reliability engineering to predict the fracture probability has been pursued by many researchers such as, the research of probability approach in the field of probabilistic fracture mechanics[4, 5], the thesis treatise of the distribution of initial crack by using nondestructive inspection method[6], evaluation for the influence of several parameters on the destruction probability or fatigue life distribution[7-11], a study on the probabilistic nature of fatigue crack propagation life[12-14], etc.

However, study on the characteristics of fatigue strength of marine propeller materials has not been made yet. In this study, we have evaluated strength characteristics of AlBC3 and HBsC1, both of which have been used for marine propellers, and presented a method of improving the strength by using air jet chisel. Then a method to predict the probabilistic distribution of fatigue life of propeller materials is presented by using a Monte Carlo simulation. Finally, the influence of several parameters on the life distribution is discussed.

2. Propeller materials

2.1 Casting of specimen material

HBsC (high strength brass casting) and AlBC (aluminum bronze casting) are two kinds of the most

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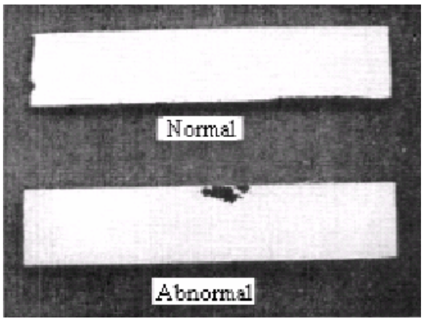

Fig. 1. Liquid penetration test for specimens.

suitable casting materials for marine propeller[15]. In this study, HBsC1 (grade 1) and AlBC3 (grade 3) were used as the specimen materials.

For manufacturing the specimens, the mold (500×250×70) was made first. The molten metal was poured into the mold at the fusion temperature, which for HBsC1 is 980℃, and for AlBC3 is 1,180℃. After about 72 hours of natural cooling, the surface of the cooled materials was processed by using a milling machine. The tip was manufactured as shown in Fig. 1 by using a cutting machine with circular wing while sufficient cutting oil was applied. The cut-off material of a specimen was processed on a milling machine to a thickness of 5.0 mm. The P.T. liquid penetration test was executed and the specimen was inspected for defects such as segregation, etc. Lastly, the material was finished by using sandpaper #1000.

There are provisions for chemical composition and mechanical properties of propeller material in the ship classification. In this experiment, all of the chemical composition and mechanical properties of propeller materials are shown in Tables 1 and 2 and satisfied ship's specifications [15] of KR(Korean Register of Shipping).

2.2 Manufacture of tensile test specimen and fatigue test specimen

The thickness of a propeller increases from the blade to the edge.

Several failures have arisen from the edge of the blade. So the shape of tensile and fatigue test specimens were made flat and given the same conditions as the edge of the blade. The dimension of tensile test specimen was manufactured as shown in Fig. 2. The thickness of specimen was 5 mm.

Table 1. Mechanical properties of specimens.

Kind		Tensile test		
		Yield strength [MPa]	Tensile strength [MPa]	Elongation [%]
Test result	HBsC1	284	500	35.6
Test result	AlBC3	280	596	27.4
KR	HBsC1	higher than 175	higher than 440	higher than 20
KR	AlBC3	higher than 245	higher than 590	higher than 16

Table 2. Chemical composition of specimens.

Kind		Composition [wt %]							
		Cu	Al	Fe	Ni	Mn	Zn	Sn	Pb
test result	HBsC1	60	0.8	0.8	0.6	0.7	Rem	0.3	0.4
test result	AlBC3	82	9.2	3.8	4.1	1.0	0.1	0.1	0.03
KR	HBsC1	52~62	0.5~3.0	0.5~2.5	lower than 1.0	0.5~4.0	35~40	0.1~1.5	lower than 0.5
KR	AlBC3	77~82	7.0~11.0	2.0~6.0	3.0~6.0	0.5~4.0	lower than 1.0	lower than 0.1	lower than 0.03

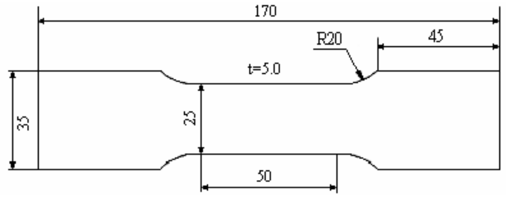

Fig. 2. Tensile test specimen.

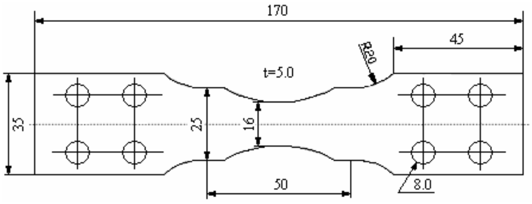

Fig. 3. Fatigue test specimen.

The dimension of fatigue test specimen is a little different. As shown in Fig. 3, 8 bolt holes and notch of 40R were processed. To make the failure happen in the middle of the specimen, to avoid the failure of grip or other parts of the specimen, and reduce the data error, the notch of long radius was given. To evaluate the notch effect, the fatigue notch factor[16] was considered.

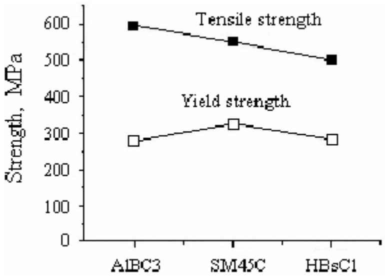

Fig. 4. Tensile test results.

2.3 Experiment method

The tensile test was determined by using a dynamic universal testing machine with a capacity of 30 ton and a speed of 5 mm/min. Considering the large variation of strength of casting products, 10 times test for each type of specimen were execused for the purpose of maintaining objectivity. The fatigue test was executed by using an electro hydraulic fatigue machine with a capacity of ±10 ton, the stress ratio of 0.1 and frequency of 15 Hz.

2.4 Experimental results and consideration

Fig. 4 represents the results of tensile testing. The tensile strength and yield strength (0.2% proof stress) are the mean value of 10 specimens' test results, respectively. The value of SM45C of the other data [17] was used to compare with the results. It was shown that the value of tensile strength and yield point of the three materials were similar.

The fatigue test results are provided in Table 3. Fig. 5 shows the relationship between specific strength and number of cycles to failure for five materials. The specific strengths of marine propeller materials are low compared with other materials. Data of SM45C, Al-alloy and Cu are quoted from the other data [17]. So the fatigue strengths of the propeller materials need to be improved. But there is currently no method for doing so.

2.5 Strength improvement

The air jet chisel is the tool used to remove rust and impurities on the metallic surface. Air jet chisel for peening is shown in Fig. 6. The peening was carried out for about 1 minute on each face of the specimen to improve the material strength. Then the face was processed by using sandpaper #1000. Fig. 7 shows the results of fatigue testing of the virgin and peened

Table 3. Fatigue test results.

No.	Alternating stress [MPa]	Fractured cycles	
		AlBC3	HBsC1
1	176.4	14832	1461
2	163.4	35583	12534
3	130.7	96609	26388
4	104.6	97139	92142
5	85.0	545213	171153
6	65.4	1311585	480136
7	45.8		4999041
8	19.6		

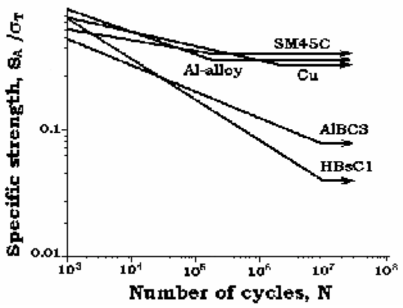

Fig. 5. Relationship between specific strength and number of cycles to failure for five materials.

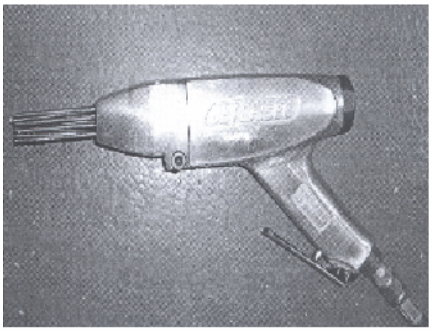

Fig. 6. Air jet chisel for peening.

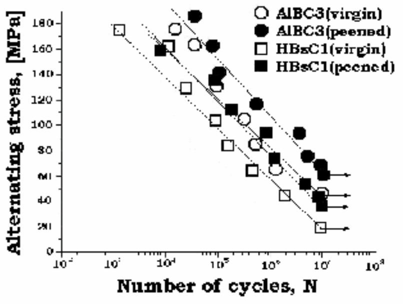

Fig. 7. Fatigue test results.

materials. Comparing the data, we can see that the fatigue life is improved by peening with the air jet chisel. The result will be discussed again in paragraph 4.3.

3. S-N Approach for fatigue life distribution

If the S-N data is linear on the log-log graph, the basic equation that represents the S-N curve is given by

$$N = \frac{A}{S^m} \tag{1}$$

Where N : number of cycles to fatigue failure, A : the intercept of the S-N curve at S equals one, ΔS : constant amplitude stress range at N, and m : slope of the S-N curve. If the S-N data is linear on one side of the logarithmic graph as in Fig. 8, Eq. (1) can also be expressed as:

$$\Delta S = A + B \log N \tag{2}$$

where log is to the base 10, N : number of cycles to fatigue failure, A : the intercept of the S-N curve, B : slope of the S-N curve, ΔS : constant amplitude stress range at N. Fig. 8 represents the $\Delta S - \log N$ curve of HBsC1.

When adding design parameters that consider safety into the equation just like Assakkaf's results [18], Eq. (2) becomes Eq. (3)

$$\log N = \frac{f_d}{B}(f_s \Delta S - A) \tag{3}$$

where f_d : damage ratio factor, f_s : stress uncertainty factor

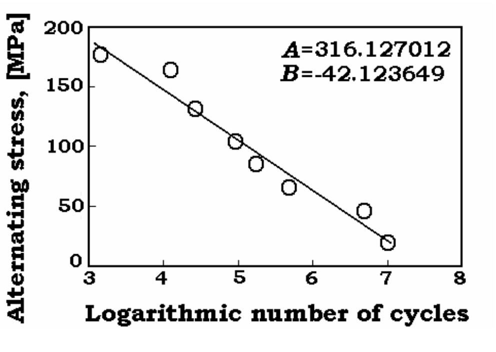

Fig. 8. $\Delta S - \log N$ curve for HBsC1.

4. Execution and results of simulation

4.1 Regression analysis for A and B

For the calculation of Eq. (2), the values of S and N that were shown in Fig. 7 were used.

Adapting the linear regression method to the $\Delta S - \log N$ curves of Fig. 7, data of A and B were obtained. The values of A and B are shown in Table 4.

4.2 Evaluation program for fatigue life distribution

For simulation, the following conditions are given:

(1) Eq. (3) was used for the calculation, because $\Delta S - \log N$ curves of propeller materials were all linear.

(2) Monte Carlo method was used in the simulation.

(3) The random number was 10000.

(4) The random variables, input data and distributions type, etc., are presented in Table 5. For COV (coefficient of variance) and distribution type, Assakkaf's results [18] are considered.

(5) The flowchart of the calculation is presented in Fig. 9.

4.3 Results and discussion of simulation

(1) Fig. 10 shows the life distributions with and without Air jet chisel peening for marine propeller materials HBsC1 and AlBC3. The mean value of alternating stress, $\mu_{\Delta S}$, was fixed at 120 MPa, and all of the COV of random variables, $COV_{\Delta S, f_d, f_s, A}$, were 0.1. The values of A and B were obtained from

Table 4. The values of A and B.

Kind	A	B
HBsC1	316.12	-42.12
Peened HBsC1	329.21	-41.17
AlBC3	367.92	-48.05
Peened AlBC3	378.57	-45.30

Table 5. Input data for simulation.

Random Variables	Mean	COV	Distribution Type
ΔS	30 MPa/ 120 MPa	0.1~0.3	Log-normal
N	1.0	0.1~0.3	Log-normal
N	1.0	0.1~0.3	Normal
A	316.12	0.1~0.4	Normal
B	-42.12	0	Constant

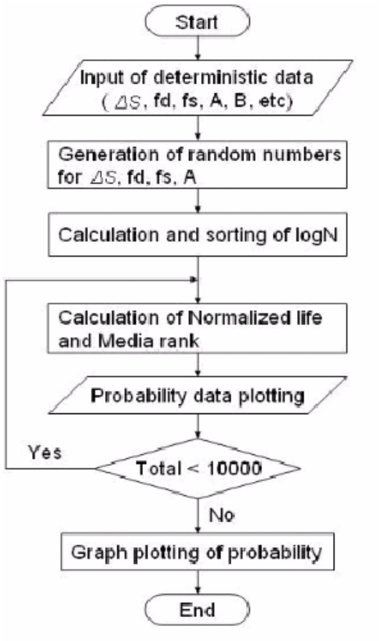

Fig. 9. Flowchart of simulation program.

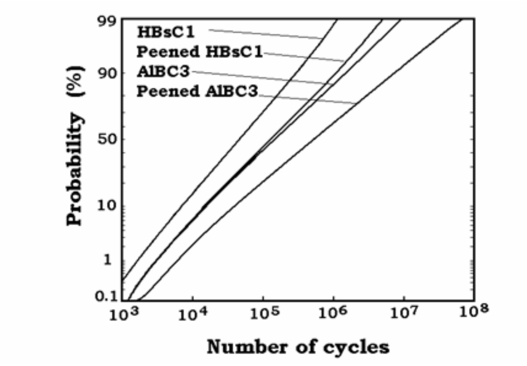

Fig. 10. Difference in life distribution for different materials.

Table 5. B was treated as the deterministic value, so COV of B was 0.

It was shown that the fatigue life of both of the materials increased after the air jet chisel peening under the same conditions. However, the life distribution shapes were not significantly changed. That is, the quantitative change of life distribution with and without peening was not so noticeable.

(2) Fig. 11 represents the effect of the alternating stress, ΔS, on the life distribution. The COV of all the random variables was 0.1, and the mean value of alternating stress was changed at 30, 80 and 130 MPa. The distribution of the life increases as alternating stress increases. The normalized number of cycles means the number of cycles divided by the mean value. The purpose is not to know the absolute value of life but to determine the distribution of life.

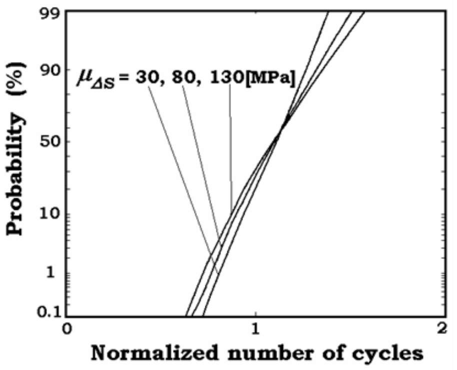

Fig. 11. Effect of alternating stress $\mu_{\Delta S}$.

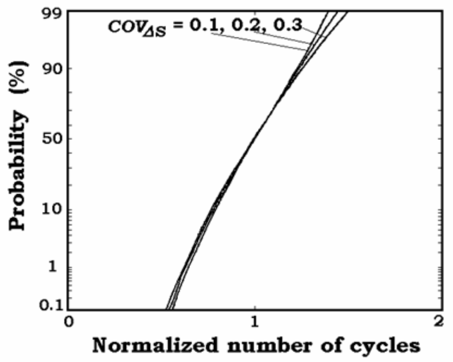

Fig. 12. Effect of COV of ΔS ($\mu_{\Delta S}$ =30 MPa).

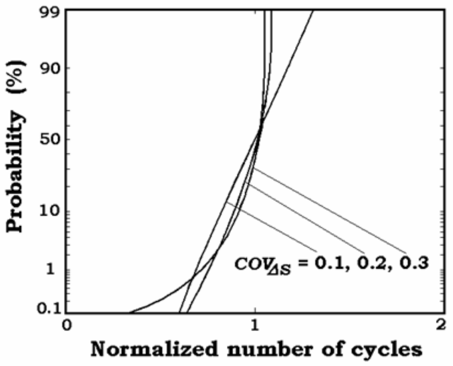

Fig. 13. Effect of COV of ΔS ($\mu_{\Delta S}$ =120 MPa).

Fig. 12 shows the effect of COV of alternating stress ΔS on the life distribution. The distribution of the life is not largely affected by the COV of ΔS, when $\mu_{\Delta S}$ =30 MPa. However, as $\mu_{\Delta S}$ is increased

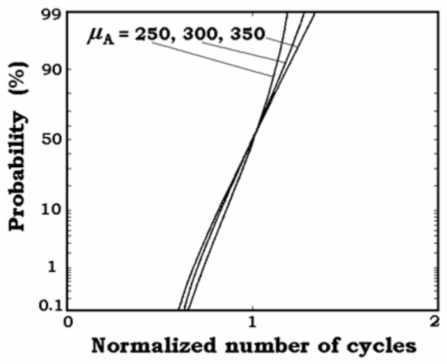

Fig. 14. Effect of the intercept A .

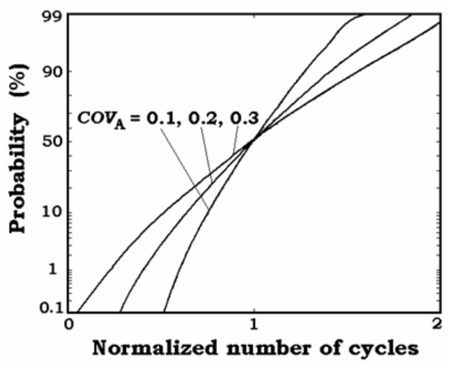

Fig. 15. Effect of the COV of intercept A .

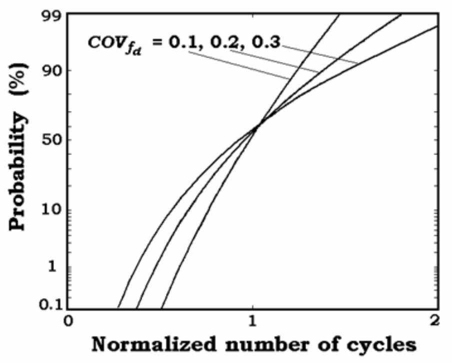

Fig. 16. Effect of damage ratio factor f_d ($\mu_{\Delta S}$ =30 MPa).

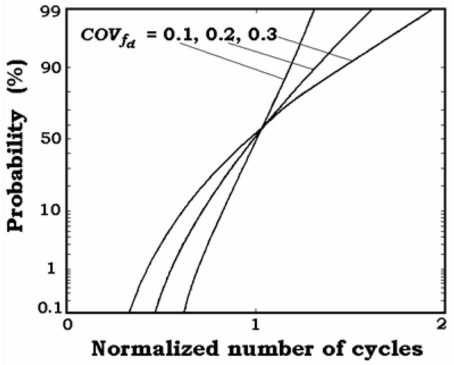

Fig. 17. Effect of damage ratio factor f_d ($\mu_{\Delta S}$ =120 MPa).

to 120 MPa as shown in Fig. 13, the influence on the life distribution is changed. As the COV of ΔS is increasing, the life distribution is increasing in the region of the low probability; however, the life distribution is decreasing in the region of high probability.

(3) Fig. 14 represents the effect of the mean value of intercept, A , on the life distribution. $\mu_{\Delta S}$ was 120 MPa, the COV of all the random variables was 0.1, and the mean intercept A , μ_A , was changed at 250, 300 and 350. We find that the influence of the mean of A is small.

Fig. 15 represents the effects of the COV of intercept, A , on the life distribution. The mean value of intercept, μ_A , was 316.12, and the alternating stress equaled 30 MPa. As shown in the figure, the life distribution increases as the COV of A increases.

(4) Fig. 16 and Fig. 17 represent the effect of the COV of damage ratio factor, f_d , on the normalized fatigue life. The mean value of damage ratio factor was 1.

The distribution of fatigue life increases as the COV of damage ratio factor increases. In Fig. 16 and Fig. 17, the mean values of alternating stress are 30 MPa and 120 MPa, respectively. There is no notable difference between Fig. 16 and Fig. 17 for the shape of life distribution. That is, the value of alternating stress, ΔS , almost has no effect on the shape of life distribution in this condition.

(5) Fig. 18 and Fig. 19 represent the difference in life distribution due to the COV of the stress uncertainty factor, f_s . The mean value of stress uncertainty factor is 1.

There was a small difference in the life distribution shape as shown in Fig. 18 when $\mu_{\Delta S}$ is 30 MPa. When $\mu_{\Delta S}$ increased to 120 MPa, there was a remarkable effect on the life distribution shape as shown in Fig. 19. The life distribution increases in the region of low probability, and the life distribution decreases in the region of high probability.

5. Conclusions

Fatigue tests were executed and a method of improving fatigue strength for marine propeller materials was suggested. In addition, a computer program was developed which predicts the fatigue life probability of marine propeller materials. The effects of different parameters on the fatigue life were discussed.

The results obtained in this study are as follows:

1. The fatigue life of both of the materials, HBsC1 and AlBC3, increased after the air jet chisel peening. However, all of the distribution shapes were not changed.

2. The distribution of the life increases as alternating stress increases. The distribution of life is not largely affected by the COV of ΔS when ΔS is small. But the life distribution increases as the COV of ΔS increases when ΔS is sufficiently large. Also as the COV of ΔS increases, the life distribution increases in the region of low probability. Life distribution decreases in the region of high probability.

3. The influence of the mean intercept A for life distribution is small. The life distribution increases as the COV of A increases.

4. The distribution of fatigue life increases as the COV of damage ratio factor, f_d, increases. And the value of alternating stress has almost no effect on the shape of life distribution in this condition.

5. When ΔS is small, there is little difference in the life distribution shape as the stress uncertainty factor, f_s, changes. But the life distribution increases in the region of low probability and decreases in the region of high probability as f_s increases and when ΔS is large enough.

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