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Prediction of Fatigue Life in 2024-T3 Aluminum Using X-ray half-value breadth

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ABSTRACT

In general, X-ray diffraction method detects the changes of crystal lattice under material surface using the angle of diffraction 2θ. This technique which deals with in the presented paper can be applied to a behavior on the slipped band or the micro crack cause to material degradation. The relation between half-value breadth and cycle numbers shows three stages, which consist of rapid decrease in the initial cycle, slight decrease in the middle cycle, and then rapid decrease in the final cycle. The ratio of half-value breadth has a constant value on $B/B_0 - N$ diagram under the loading condition except early part of fatigue life. The ratio of half-value breadth B/B_0 with respect to number of cycle to failure N_f has linear behavior on $B/B_0 - \log N_f$ diagram. Therefore, the evaluation of fatigue life by the average gradient has much less mean error than the estimation of fatigue life by $\log B/B_0 - \log N/N_f$ relation.

Keywords : X-ray diffraction, Half-value breadth, Diffraction angle, Average gradient, Individual gradient, Cycle ratio

1. Introduction

Though the consumption efficiency for machine or structure has been much more required by means of the development of the analytical engineering, the fracture or the failure for a mechanical structure that is subjected to the repeating loads have continually been taken place. Especially, as more developing of the method of engineering analysis, the degradation of the safety leads to a defect, where the surface or its under exists, brings about a fatal fatigue damage. Thus, non-destructive parameters are required to check as a result of fatigue damage, which lead to characteristics of the material changes, the micro cracks, the growth properties, and then after these the transition of macro cracks. (1)

The fluorescence and magnetic searchlight (2) are very available to search for defects where exist material surfaces and its inners. However, it is inadequate to probe the initial fatigue failure. That is, in the initial region of fatigue life, because there occurs the cyclic slip band and the micro cracks and the growth, which outbreak by means of this. A physical parameter that is very sensitive the local changes such as the grain deformation are systematically required for the monitoring. Thus, in order to apply fatigue failure to above described the method, there have large difficulties at the used material or the experimental method.

X-ray diffraction method detects the changes of crystal lattice under material surface using the angle of diffraction 2θ. That is, this method is very sensitive on the crystal deformation, which causes to the behavior on slip band and micro crack at the initial region, and thus can sufficiently detect material deterioration depending on the iteration number (number of replication) N such as fatigue life. Partly, the mechanical structural material which was generally used is occurred the distortion of crystal lattice due to machining or heat treatment and at the same time leads to fine residual stresses. (3) But, fatigue failure occurs in the inner material can release the distortion of crystal lattice and has favor correspondences between half-value breadth B of X-ray parameter and the iteration number N of fatigue damage. A remarkable study of research results represent as follows.

In accordance to the research, Hira, *et al* [4] , when investigating the result using the X-ray irradiation with annealing the Carbon steel 0.76%C, validated that the measurement of half-value breadth for the initial value during at that time, B/B_0, increase by the three stages on processing the fatigue. And when examining the fatigue test result for the machining material using the X-ray irradiation without annealing the Carbon steel 0.25%C, Hira, *et al* [5] reported as iteration number was increased decrease by the three stages. In addition to, the ratio of half-value breadth B/B_0 is increasing by the three stages at the experiment including the annealing the Carbon steel 0.22%C [6] and indicated the ratio of half-value breadth B/B_0 and fatigue life that indicates the algebra logarithm ratio $\log N/N_f$, which represents the ratio of the then iterative number for the fracture iteration number has little relation with the stress amplitude and shows the linear behavior.

The main result of this texture expresses the material fatigue damage can be predicted by using help-value breadth ratio B/B_0. The above illustrated studies have represented that the relations between help-value breadth ratio B/B_0 and fatigue life ratio of the logarithm ratio $\log N/N_f$ are expressed as a straight line without respect to the magnitude of the loading stress because it is not completely considering the effect by the loading stress. However, when half-value breadth B/B_0 that depends on the increment of fatigue life ratio of the logarithm ratio $\log N/N_f$ was subjected to the loading stress around or at much larger fatigue limits, the results show very different aspects. So, to compensate these things, a new evaluate method for fatigue life is required these day.

Consequently, the purpose of this paper intend to suggest that the new evaluate method for fatigue life can consider the magnitude of loading stress using N_f line which is based on the average gradient (slope) of half-value breadth ratio B/B_0 for iterative number $\log N$ and half-value breadth ratio B/B_0 in the case of the fracture in order to overcome the defects the existing method for fatigue life which was evaluated.

2. Experimental Instrument and Methods

2.1 Materials and Specimen

In this study Materials that are used have a thickness 5mm an aluminum alloy plat A2024-T3 that have been used in the field of the structural aircraft materials. Using the chemical and mechanical properties was listed in Table 1 and Table 2 respectively.

Table 1 Chemical compositions of 2024-T3 aluminum (wt.%)

Material	Cu	Mg	Mn	Fe
2024-T3	4.82	1.67	0.58	0.18
Si	Cr	Zn	Ti	Al
0.07	0.02	0.06	0.15	Bal

Table 2 Mechanical properties of 2024-T3 aluminum

Material	Yielding strength σ_{ys} (Mpa)	Tensile strength σ_{ts} (Mpa)	Elon-gation ε_f (%)	Young's modulus E (Gpa)
2024-T3	380	507	21.6	77.02

To get the mechanical property, the tension test was conducted by using the Universal Material Testing Machine (Instron model 1337 type). The shapes of specimens were in Figure. 1(a). In Figure. 1(b), Fatigue specimen was worked by the milling machine with identifying the maximum bending load with the direction of the rolling and cut with the volume size, 92mm × 32mm × 4.2mm. This specimen shape should be the radius of curvature, $\rho \cong 39$mm to become the stress concentration factor $K_t \cong 1.4$ by considering the grip size between the diagram of the stress concentration factor and the bending fatigue tester which was suggested by Peterson [7].

2.2. Fatigue Experiment

Figure. 2 show the schematic diagram of the Schenck type of the plane bending fatigue tester (Mori testing machine Co. model 5171). The maximum bending moment is 2kgf-m and the revolution per minute is 1500 rpm. The experimental control method is conducted the load control type which can be the average stress "zero" and the stress amplitude σ_a is 303Mpa, 262Mpa, 225Mpa, and 180Mpa respectively.

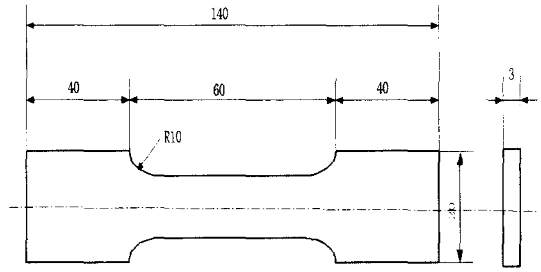

Fig. 1(a) Tension test specimen

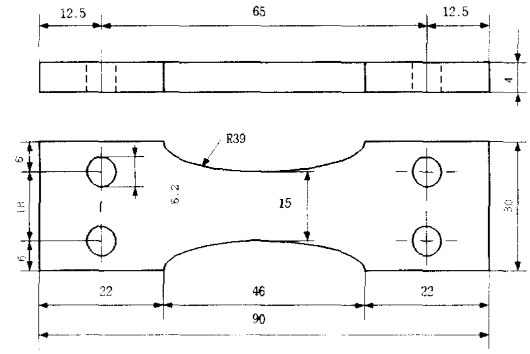

Fig. 1(b) Fatigue test specimen

Fig. 1 Geometry and dimension of test specimen (unit: mm)

According to increase iteration number N, it occurs at the center of the specimen. And the propagating the distribution of the surface micro crack and length were observed using 150 times of image analysis system (Image pro-plus) within an arbitrary fixed area, 5mm × 12mm.

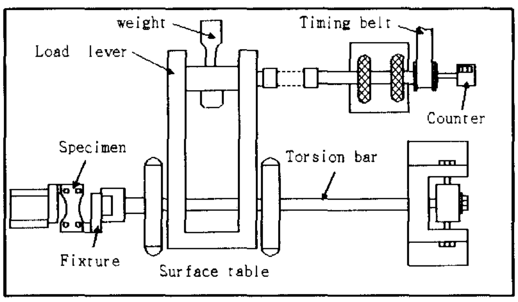

Fig. 2 Schematic illustration of fatigue test machine

2.3 X-ray Diffraction Experiment

The factor of the surface conditions has a crucial effect on X-ray half-value width B because of measuring the tiny plastic deformation whose the specimen surface. Thus, the machining residual stress that occurs for cutting the specimen was eliminated by using the method of the Electrolytic Polishing.

Further, its crystal lattice structure has face cubic construction (FCC) because an aluminum alloy A2024-T3 have the main ingredient aluminum of the atom number 13 and the grain distance of a specific crystal face (h,k,l), d is expressed as next equation (1).

$$\frac{1}{d^2}=\frac{h^2+k^2+l^2}{a^2} \qquad (1)$$

As mentioned above, the crystal constant of the aluminum alloy A2024-T3, a =4.0497Å. The exponents of a specific crystal h,k,l are involved in the diffraction by only both odd and even faces because the crystal lattice structure of the aluminum A2024-T3 has FCC. [8]

Figure 3 is showing that the intensity of X-ray is bigger and can occur X-ray diffraction if X-ray which was incident on the material surface and the incident X-ray wavelength is identified with the X-ray between an arbitrary atom line and the next its distance. This is called the Bragg's law, that is, the equation is expressed as:

$$n\lambda = 2d\sin\theta \qquad (2)$$

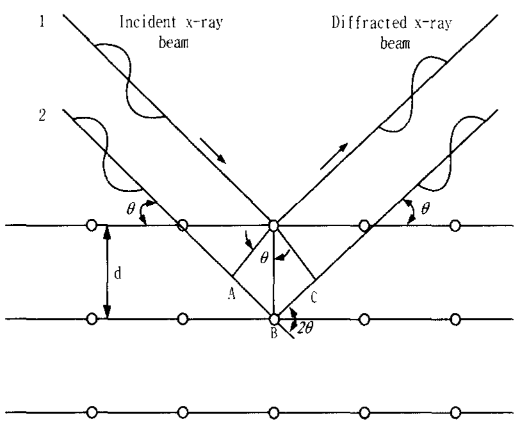

Fig. 3 Schematic illustration of X-ray diffraction in crystal lattice structure

Where, n indicates the reflection order, which is a positive integer, generally use "1". λ Means K_α -ray's wavelength, that is the characteristic X-ray, of the Cu target that was used the X-ray generator. The value is 1.540562Å.

In addition, in order to precisely measure X-ray parameter is required as follows:

(1) the Diffraction angle 2θ should be satisfied with possible around 180° , (2) a higher diffraction intensity, and (3) an independent peak. In this paper, already as mentioned above, by considering the sufficient conditions, the diffraction angle 2θ is determined as following method:

From equation (2), arranging by $1/d$.

$$\frac{1}{d}=\frac{2\sin\theta}{\lambda} \tag{3}$$

$$\frac{4\sin^2\theta}{\lambda^2}=\frac{h^2+k^2+l^2}{a^2} \tag{4}$$

Thus, the diffraction angle 2θ can represent the equation (5) by using the illustrated above equation (4).

$$2\theta=2\cdot\sin^{-1}\sqrt{\frac{\lambda^2}{4}\cdot\frac{h^2+k^2+l^2}{a^2}} \tag{5}$$

Table 3 indicates the X-ray experimental conditions to measure X-ray parameter and Figure 4 represents the diffraction profile of when an aluminum alloy Al 2024-T3 was linked with the X-ray diffraction generator , which is called Goniometer, by $2\theta-\theta$ system from 134° to 141° . In figure. 4, drawing the parallel reference line on the diffraction intensity curve of the background and the parallel reference line in the 1/2 distance from the maximum diffraction intensity curve, the center of angle is 2θ and the breadth ratio is B .[9] Likewise, the experimental diffraction angle $2\theta_{ex}$ has the diffraction peak at 137.64° and occurs the error 0.24° between the theoretical diffraction $2\theta_{th}$. However, this error is ignored within the sufficient engineering error.[10]

Table 3 X-ray diffraction condition of Al 2024-T3 aluminium

Test condition	Parallel-beam method
Diffraction angle	137.44°
Characteristic X-ray	Cu- K_a
Diffraction plane	(422)
Filter	Ni
Tube voltage	35kV
Tube current	30mA
Irradiated area	1× 7mm
Soller slit	1°
Scanning speed	2° /min
Chart speed	40 mm/min
Time constant	2 sec

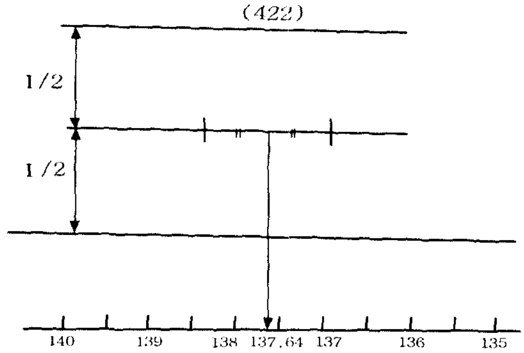

Fig. 4 Determination of diffraction angle 2θ at X-ray diffraction profile for Al 2024-T3 aluminium

3. Experimental Results and Discussion

3.1 σ_a-N Curve of Aluminum alloy Al 2024-T3

Figure. 5 discloses the relationship between the stress amplitude σ_a and the replication number N to determine the fatigue strength of the aluminum alloy Al 2024-T3. [11] In general, the steel materials form the break point of σ_a-N Curve and use the fatigue limit of infinite life concepts. But, the aluminum alloy Al 2024-T3 that was used in this research didn't occur the break point even though the iteration number N 's value is 2×10^7. Therefore, the fatigue strength σ_w in Figure. 9 was obtained to by conversing the time strength for the iteration number, $N=1\times10^7$ into the fatigue strength and the value was 180Mpa.

In the initial region, major micro cracks and its growth were taken place on the specimen surface. And when the maximum crack length reaches to an extent once or twice of the crystal size that is the range of 80 μm , the time which occurs the micro crack defined within the investigation of X-ray domain and expressed as " • ". Observing the surface of specimen by using the image processing system with the 150 times of the amplification, the generation time, N_i exists in 10~20%. This result has the same trend as comparing with the previous studies [12] which was conducted with the result of the structural carbon steel material S25C.

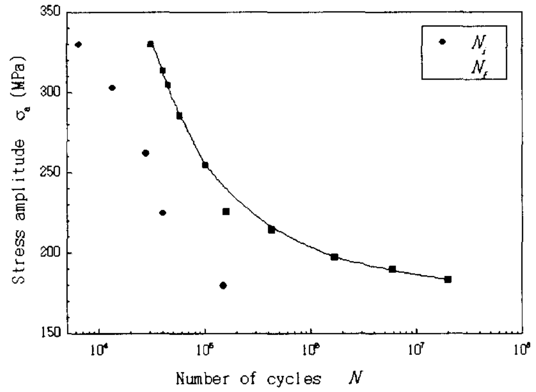

Fig. 5 $\sigma_a - N$ curve for 2024-T3 aluminum

3.2 The Variation of half-value Breadth for Iteration Number

Figure. 6 represents the variation of X-ray diffracted ray breadth according to the iteration changes an aluminum alloy Al 2024-T3. As illustrated Figure. 6, the changes of half-value breadth have little, but just thereafter they were gradually decreased until the value of an iteration number come to about 2×10^5 which is predicted from the starting point of the fatigue origination, in the stress amplitude value of the around fatigue limit at σ_a = 180MPa. These results show the same results that Hira, *et al* [13] obtained in reference [13]. In addition to, half-value breadth rapidly decreases at the comparative high stress amplitude over than fatigue limits and then shows a slow due. And again, abruptly went down at the last stage. From this tendency it is clear that the stage point in starting to change the initial fatigue life of half-value breadth, B putting together with the partial variation have a loss by dislocations or lattice defects which cause to the fatigue and become energetically a stable condition. But for the annealed carbon steel of 0.76%C [4], half-value breadth rises up rapidly in the fatigue initial stage and thereafter generates a slow increment and again swiftly increases at the end stage. From these relations we can be found that half-value breadth B is a quiet dependable parameter as the material characteristics.

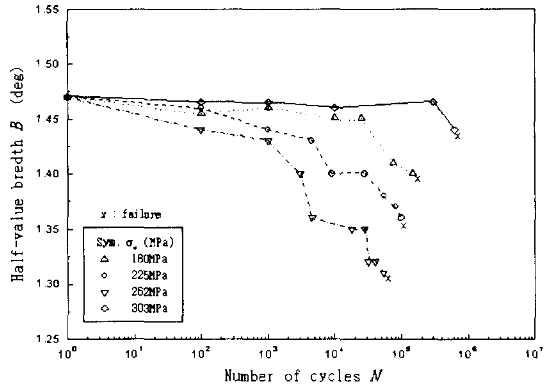

Fig. 6 Change of half-value breadth during fatigue process

3.3 Prediction Fatigue life ratio, N/N_f by Half , value breadth ratio, B/B_0

3.3.1 Using the method of the relations, $B/B_0 - \log N/N_f$

Figure 7 describes the relationship between the logarithms of iteration ratio, $\log N/N_f$ and Half-value breadth ratio, B/B_0 , that is the plot equation, after excluding the initial region of fatigue life which has little change, which were obtained by multiplying each data with using the minimum square method.

According to a previous research of Hira, *et al* [4,5], the relations, $B/B_0 - \log N/N_f$, can generate a line regardless the stress amplitude, and can be represented as follows:

$$B/B_0 = -0.02754\log(\frac{N}{N_f}) + 0.93014 \qquad (6)$$

Equation (6) shows that by measuring half-value breadth, B/B_0 , can be predicted fatigue life non-distractively. But, as above Figure 7, the stress amplitude of the around fatigue limit, the data σ_a = 180Mpa is different a relatively high stress amplitude of data. Exactly, the regression equation of the $B/B_0 - \log N/N_f$ has a larger error by the means of σ_a = 180Mpa data and thus to reduce the error, it should be excluded. Hence, it is considered that the above explained method brings about a quiet error to predict fatigue life due to the stress amplitude of the around fatigue limit.

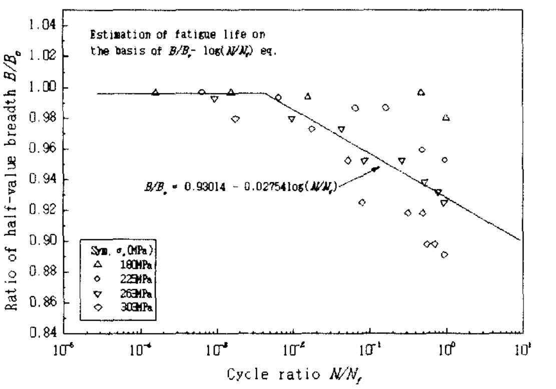

Fig. 7 Relation between ratio of half-value breadth B/B_0 and cycle ratio N/N_f

3.3.2 Using the methods of half-value breadth gradient and the diagram N_f

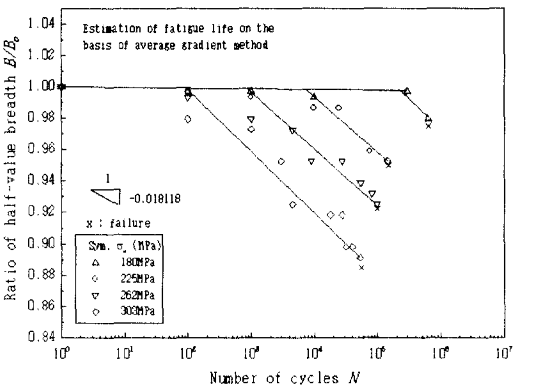

Fig. 8 Estimation of fatigue life on the basis of average gradient method

Figure. 8 shows half-value breadth for the iteration of logarithm $\log N$, to begin with drawing the horizontal line at half-value breadth B/B_0 with the value, 1.0 and indicates the average gradient by making the minimum square method into a repression line with using the data in correspond with each stress amplitude was obtained with regard to the reference that is half-value breadth B/B_0 with the value, 1.0, by using the data which were changed by half-value breadth B/B_0. The gradient value for each stress amplitude exists between –0.00283 and -0.034287 and the average slop is –0.018118. Therefore, changes of half-value breadth B/B_0 with respect to a replication number on the replication number of logarithm diagram $\log N$ can express as a nearly constant gradient straight line, which doesn't depend on the stress breadth σ_a . Herein, Estimation of fatigue life on the basis of average gradient was defined as the evaluation method.

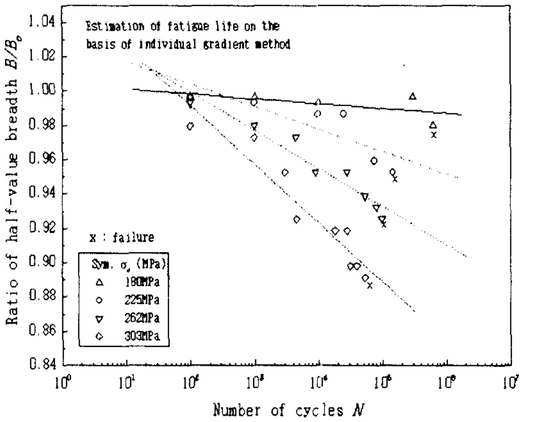

Fig. 9 Estimation of fatigue life on the basis of individual gradient method

As shown in Figure. 9, the half-value breadth B/B_0 for replication number of logarithm $\log N$, the data that doesn't generate the change of gradient at the initial fatigue life abbreviates and used the rest of data. From figure, the straight line indicates a specific value which was exhibited by using the minimum square method into a repression line for the data in correspond with each stress amplitude and the half-value breadth B/B_0 generates the changes from the initial domain., the starting point for the changes has an identity value regardless the stress amplitude .The gradient value for each stress amplitude exists between –0.0034 and -0.018421 , and if each stress amplitude is greater, the gradient value is bigger. These results show that the half-value breadth of the initial fatigue life portion is associated with the changes by the arising slip band and growth for the grain changes within the grain tran crystalline. Since then the half-value breadth of the fatigue life portion is relevant to fined-grain status. In case, the former generates that the half-value breadth of the initial fatigue life portion has an equal value regardless the stress amplitude but the latter shows that the more half-value breadth of the initial fatigue life portion is bigger, the greater changes are. In this research, the method is defined, what is called, the estimation of fatigue life on the basis of individual gradient.

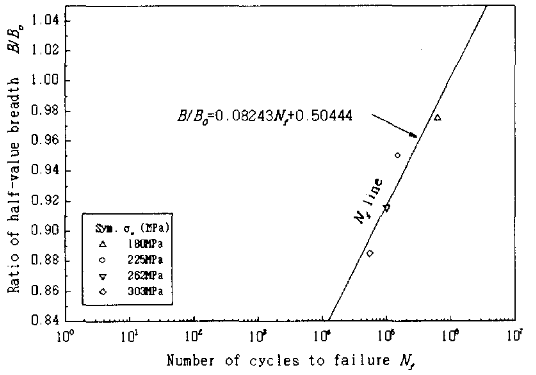

Fig. 10 Relation between B/B_0 and N_f for various stress amplitude σ_a

Figure. 10 show that changes of half-value breadth B/B_0 with respect to a fractural replication number for the replication number of logarithm diagram $\log N_f$. The straight line N_f in figure. 10 define. On the figure, the smaller the stress amplitude is, the minor changes of half-value breadth B/B_0 for the straight line N_f are and the data were distributed toward a right upper direction. The obtained data were carried out as the following procedures:

First, a half-value breadth B/B_0 at any replication number N was marked at the diagram $B/B_0 - N$, relation between B/B_0 and N_f for various stress amplitude σ_a.

Second, the N_f of Figure. 10 can be represented in the diagram $B/B_0 - N$.

Third, the N_f line draw any point on the straight line with the gradient which was obtained by the Estimation of fatigue life on the basis of average gradient in Fig.8 into the second point on the straight line with the slop which was exhibited by the estimation of fatigue life on the basis of individual gradient.

Fourth, in third procedure, the encountering point by drawing the intersected point on N_f line into a perpendicular line at the N axis is the fractural replication number, N_f for the used stress amplitude.

Fifth, in forth procedure, we can get the fatigue life ratio for any replication number N by dividing any replication number N for the fractural replication number, N_f.

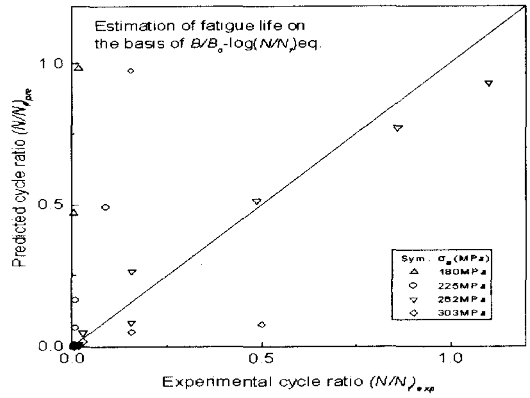

Fig. 11(a) $B/B_0 - \log N/N_f$ equation

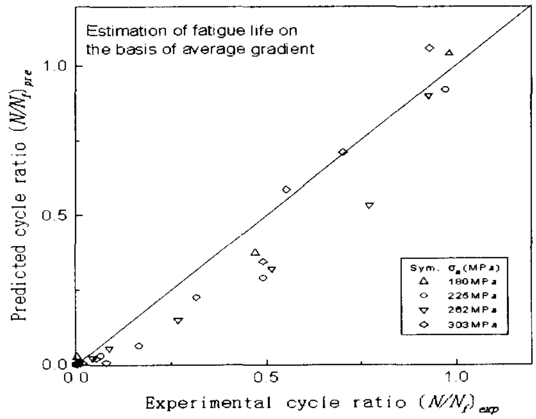

Fig. 11(b) Average gradient method

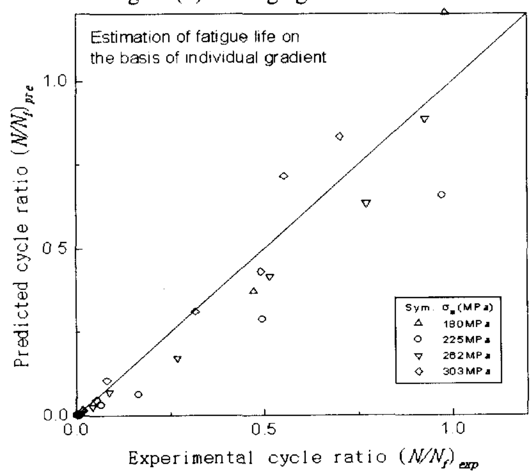

Fig. 11(C) Individual gradient method

Fig. 11 Relation between predicted cycle ratio and experimental cycle ratio

Figure. 11 represents that the results which were compared between the predicted fatigue life ratio $(N/N_f)_{pre}$ and the experimental fatigue life ratio $(N/N_f)_{\exp}$ as above explained procedure method carry out the evaluation for each case using the estimate average error[10] which was defined by the next regulated equation (7).

$$\psi = \frac{\left|(N/N_f)_{\exp} - (N/N_f)_{pre}\right|}{(N/N_f)_{\exp}} \times 100(\%) \qquad (7)$$

The previous method such as Figure. 11(a) by the equation $B/B_0 - \log N/N_f$ is carrying out much greater evaluation error, the estimate average error extent 400.22% the experimental fatigue life ratio for the predictive fatigue life ratio between the experimental fatigue life ratio $(N/N_f)_{\exp}$ and the predictive fatigue life ratio $(N/N_f)_{pre}$. Especially, the region of the excluded initial fatigue life data using when the regression equation can't almost predict. However, the estimation of fatigue life on the basis of average gradient such as Figure. 11(b) and the estimation of fatigue life on the basis of individual gradient such as Figure. 11(c) have 15.57% and 16.86% respectively. Thus the former of the estimate average error is smaller 1.29% than the latter. And comparing when the method as shown in Figure 11(a) to the other method as shown in Figure. 11(b), the estimate average error has 26 times greater. Therefore, the results show that the evaluative fatigue life method how to use of the previous relations $B/B_0 - \log N/N_f$ has a quiet evaluative error.
Whereas, the estimation of fatigue life method, as shown in Figure. 11(b) and (c), shows that the predictive fatigue life ratio is generally in accord with the experimental fatigue life ratio. But, after middle portion, when comparing to each data, we can know that the Estimation of fatigue life on the basis of average gradient is more available than the estimation of fatigue life on the basis of individual gradient in terms of predicting fatigue life. Thus, from the results generate that the estimation of fatigue life on the basis of individual gradient excludes the data with no changes of half-value breadth, relatively when comparing to the Estimation of fatigue life on the basis of average gradient is including the initial region data. And, in contrast with the estimation of fatigue life on the basis of individual gradient should know each gradient of the stress amplitude, the fatigue life can simply predict by applying a common slop to the individual stress amplitude in the Estimation of fatigue life on the basis of average gradient. Thus, the Estimation of fatigue life on the basis of average gradient is very useful method that predicts the material fatigue life in materials that is subjected to fatigue damage.

4. Conclusions

With using X-ray diffraction in order to predict fatigue life, we conducted the plane bending moment test for fatigue life about the aluminum alloy Al 2024-T3 that has been used for the aircraft structural material and continually measured the X-ray breadth as result of an increment of the replication number. And examining into the relations between the extent of damage and X-ray breadth, the conclusions are as follows:

1. When increasing the replication number, the half-value breadth B shows three portions excluding the stress around fatigue limit. The results represent a rapid decrease in the initial region, a slow drop in the middle portion, and a swift declination in the last portion.
2. When excluding the stress around fatigue limit, changes of the half-value breadth ratio B/B_0 can express as the average gradient for each of stress amplitude on the replication number of a logarithm $\log N$ regardless the load condition.
3. When predicting the fatigue life Using the logarithms of iteration ratio, $\log N/N_f$ and the half-value breadth ratio, B/B_0 , the estimating error becomes 400.22% by the initial fatigue life data. Thus, this value quiet escapes from the engineering error range.
4. When comparing the existing method that has been used relations between $\log N/N_f$ and $\log B/B_0$ for the total stress amplitudes to the new method that uses relations between $\log N$ and the diagram of $\log B/B_0$ for each of stress amplitude, the estimating error is decreasing about 26 times.

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