Study on Crack Growth Behavior in Impact Fatigue

Part III, Fatigue Crack Growth Behaviors of 2017-T3 Aluminum Alloy*

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Impact fatigue crack growth behaviors were investigated by using 2017-T3 aluminum alloy, one of the representative f.c.c. metals for mechanical structure, as an experimental material under the stress ratios $R=0$ and -1 . Results are discussed in comparison with those obtained under non-impact fatigue done under the same stress ratios.

It is made clear, on $\log da/dN$ - $\log K_{max}$ diagram, that da/dN in impact fatigue is higher than that in non-impact fatigue under both stress ratio conditions. Furthermore, such a discrepancy in da/dN due to the difference in the stress condition does not disappear in the evaluation done based on the effective stress intensity factor range ΔK_{eff} . And, peculiarities of impact fatigue crack growth behavior obtained in this study well resemble those for low carbon steel demonstrated previously by the authors.

It is concluded that the effect of the compressive load in impact fatigue loading of $R=-1$ on da/dN is smaller than that in non-impact fatigue.

Key Words: Impact Fatigue, Impact Compressive Stress, Fatigue Crack Growth Rate, Crack Opening Behavior

1. Introduction

The authors conducted a series of experiments on impact fatigue crack growth behavior of low carbon steel conforming to JIS. S10C and the results obtained were reported in previous papers¹⁻². In the second report of this study using an improved fatigue testing machine which can produce a stable simple pulse type impact stress pattern, crack growth and crack closure behavior in impact fatigue were investigated. The results show that the fatigue crack growth rate is higher in impact fatigue than in non-impact fatigue when compared on da/dN - ΔK diagram and this difference does not vanish even when rearranged against effective stress range ΔK_{eff} . The fact that the fatigue crack growth rate is higher in impact fatigue than in non-impact fatigue, when plotted against ΔK , was already demonstrated in

authors' first study under the complicated impact stress pattern accompanied with damped stress variation¹, and several investigators also reported on such a crack growth behavior in impact fatigue^{3,4,5}.

Main purpose of the present study is, first, to verify whether or not the above-mentioned trend recognized with low carbon steel can be found with aluminum alloy 2017-T3, one of representative f.c.c. metals; secondly, to observe the influence of stress ratio through impact fatigue crack growth tests under the stress ratios of $R=0$ and -1 . Here, crack closure behavior is also observed by means of unloading elastic compliance method. Results are discussed in comparison with those under non-impact fatigue.

2. Experimental Material and Procedure

The material used in this study is 2017-T3 aluminum alloy, whose chemical composition and mechanical properties in static tensile test are listed in Tables 1 and 2, respectively. The supplied 2.5mm thick plates were machine-finished to the shape and sizes of specimen as indicated in Fig.1. The average grain size of the material was about 30 μm . Both faces of the specimen surface near the center notch were electro-polished by about 20 μm after emery paper polishing. Then, to facilitate crack observation, the specimen surface was lightly polished in the axial direction with high grade emery paper.

Experiments under impact and non-impact fatigue loads were carried out with a testing machine of about 60 Hz. in loading

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Table 1 Chemical composition of the material

Material	Chemical Composition (%)									
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Al
2017-T3	0.32	0.22	4.08	0.45	0.47	0.01	0.02	0.02	0.00	Bal.

Table 2 Mechanical properties of the material

Material	0.2% proof stress $\sigma_{0.2}$ MPa	Tensile strength σ_b MPa	Elongation δ %
2017-T3	303	426	20.0

Fig.1 Shape and sizes of the specimen

Fig.2 Working principle of the push-pull type impact fatigue testing machine

frequency, the same as the one used in the previous study². Working principle of the machine is shown in Fig.2 schematically. Details are available elsewhere^{2,6}.

Examples of impact stress patterns obtained with this testing machine are shown in Fig.3 (a), (b). These were detected with the load cell shown at the right hand side of the specimen in Fig.2.

It is confirmed that stress patterns detected with the load cell have no difference from those at the center of the specimen. Fig.3 (a) is the pattern under the stress ratio $R=0$ and (b) the one under $R=-1$. Impact stress pattern was held constant during the experiment. But, the magnitude of impact stress tended to become smaller slightly according to crack growth, so the clearance between impact ball and rigid wall was adjusted to keep the stress value constant during the experiment.

Magnitude of stress variation near $\sigma=0$ being somewhat larger in the case of $R=-1$ than in the case of $R=0$, such a stress variation of low amplitude is disregarded in the following discussion. Besides, the stress rising time of both patterns is about 1 millise.

Fatigue crack closure behavior was observed by using the strain gages cemented just beneath crack growth path as shown in Fig.4. And, strain gage to monitor the load is cemented apart from growth path by about 15 mm as shown in Fig.4. Output voltages of these strain gages were put into the substruction circuit to obtain a compliance curve, whose examples are shown in Fig.5. Strain gages to monitor the displacement were used after the crack propagated on the strain gage to observe the crack opening level clearly. Compliance curve obtained by this method is clearer, especially in the case of impact stress condition, than that obtained with which the compliance curve was obtained in previous study. Besides, it was confirmed that these two strain gages gave the same crack opening level in spite of the difference in the position.

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

Fig.3 Examples of impact stress patterns

Observation of the crack length was done by taking replica of specimen surface with acetylcellulose film after the total crack length reached about 6 mm without interrupting the experiment. Prior to fatigue crack growth tests, fatigue precracks up to total length of 4 mm were introduced under the non-impact stress condition with stress amplitude below the maximum tensile stress of fatigue crack growth test. Measurement of crack length was done referring to E647-81 recommended by ASTM.

Fig. 4 The location of strain gages cemented for detecting U

Fig. 5 Examples of compliance curves

3. Experimental Results and Discussion

3-1. $da/dN - K_{max}$ relation

In this study, stress intensity factor K is calculated by the following equation proposed by H. Tada for both load conditions;

$$K = \sigma \sqrt{\pi a} (1 - 0.025 \lambda^2 + 0.06 \lambda^4) \times \sqrt{\sec(\pi \lambda / 2)} \quad (1)$$

$$\lambda = 2a/W$$

where a is half crack length and W sheet width.

The reason why the same equation was used to determine the value of K regardless of the difference in the load condition was given in the first study¹. Recently, K. Kishimoto, et al.⁸ suggested in their study on evaluation of the value of K under dynamic stress condition, K_D under three point impact bending that numerical difference between the values of ordinary K and K_D is negligible when the rising speed of the stress is as low as in this experiment. Therefore, it is valid to discuss fatigue crack growth behavior under both types of load conditions based on the value of K obtained with Eq. (1).

Figs. 6 and 7 show relations of da/dN versus K_{max} in impact fatigue and in non-impact fatigue, respectively.

Two solid lines in Fig. 6 were drawn to run smoothly the center of the scatter bands of $R=0$ and -1 , respectively. These curves are also drawn in Fig. 7 by dashed line to make comparison easier. From Fig. 7, it can be concluded that the crack growth rate da/dN is higher in impact fatigue than in non-impact fatigue for same levels of K_{max} in both cases of stress ratios. Especially in the case of $R=-1$, this trend is distinct in low K_{max} region, but the difference in da/dN under both load conditions becomes vague with an increase in

Fig. 6 Relationship of da/dN and K_{max} in non-impact fatigue

Fig. 7 Relationship of da/dN and K_{max} in impact fatigue

K_{max} . And, Fig.7 (a) shows appreciably well the applied stress range dependence of impact fatigue crack growth rates as is demonstrated in the previous study done with low carbon steel, but such a trend was not found in the case of $R=-1$ shown in Fig.7 (b).

Fig.8 shows the effect of stress ratio on $da/dN-K_{max}$ relation; (a) is the results in non-impact fatigue represented with the center lines of scatter bands indicated in Fig.6, and (b) is those in impact fatigue done with the scatter bands as indicated in Fig.7 because of the existence of the stress range dependence.

Fig.8 (a) shows that compressive stress contributes to acceleration of crack growth rate in non-impact fatigue, as is already pointed out by Y. Naito, et al. in their experiments conducted using carbon steel JIS. S45C and alloy steel JIS. HT80⁹ and by R. Murakami using ZK141F aluminum alloy⁴. On the other hand, from Fig.8 (b), stress ratio effect in impact fatigue is observed in low K_{max} region but such a difference comes to be eliminated with an increase in K_{max} value. From the above facts, the following conclusion can be derived, that is, the contribution of the compressive impact stress to $da/dN-K_{max}$ relation in impact fatigue is less than in non-impact fatigue.

3-2, Crack closure behavior and evaluation with effective stress intensity factor range

Crack opening ratio U was determined by the method described before. Dependence of U on K_{max} is shown in Fig.9. Fig.9 (a) shows that the value of U under non-impact fatigue increases with an increasing K_{max} and reaches a saturated value beyond the value of K_{max} of about 10 MPa $\sqrt{m}$. The value of U in impact fatigue also increased with K_{max} and saturates gradually as is seen in Fig.9 (b). And in case of impact fatigue with $R=0$, the stress range dependence of U is recognized in the range of $K_{max} \geq 8$ MPa $\sqrt{m}$ and the higher the value of stress σ_{max} is, the larger the crack opening ratio U is. This stress range dependence is not recognized in the results with $R=-1$, but the scatter is wider than that in non-impact fatigue as a whole.

Relations between da/dN and ΔK_{eff} are shown in Figs.10 and 11 for both load conditions, where the value of ΔK_{eff} is calculated as ΔK multiplied by U . At first, comparing Fig.10 with Fig.6, the difference in crack growth rates between the stress ratio conditions of $R=0$ and -1 is rather small when using ΔK_{eff} , but influence of R is still evident. Besides, $da/dN-\Delta K_{eff}$ relations under both stress ratios show a trend to converge to straight lines with slope of $m=2.4$, respectively. On the other hand, all of the results in impact fatigue well lie on a straight line of $m=2$ except for the results in ΔK_{eff} region less than 4 MPa $\sqrt{m}$ regardless of the difference in stress ratio as shown in Fig.11. Furthermore, the dependence of da/dN on applied stress σ_{max} , which is observed in Fig.7, vanishes. This fact shows that the crack growth rate can be

Fig.8 Schematic diagrams to indicate the effect of compressive stress in $da/dN-K_{max}$

Fig.9 Relationship between U and K_{max} under both stress conditions

better evaluated when plotted against ΔK_{eff} than against ΔK . When the results in impact fatigue are compared with those in non-impact fatigue, which are represented by dashed line and a chain line in Fig.11, it is clear that the value of da/dN is distinctly higher in impact fatigue than in non-impact fatigue. Such a trend is prominent in low ΔK_{eff} region, and is similar to the case shown in Fig.7 plotted against K_{max} . Thus, the following conclusion can be derived; the difference in da/dN depending on the load pattern can not be evaluated uniformly even with the effective stress intensity factor range.

Fig.10 $da/dN-\Delta K_{eff}$ in non-impact fatigue Fig.11 $da/dN-\Delta K_{eff}$ in impact fatigue

3-3, Fractographical observation

Observations on fracture surface under both load conditions were also carried out with SEM to examine the above-mentioned conclusions from a fractographical point of view. But there is not found any distinct difference in morphological feature of fractured surface under both types of loading conditions and most of the area consists of striations or non-characteristic parts regardless of the difference in load pattern, whose examples are shown in Fig.12. And intergranular facets as shown in Fig.13 are also observed with low area ratio less than 10 percent. Some reports say that a difference in crack growth rate between impact fatigue and non-impact fatigue reflects on striation spacing⁴. But, observations on striation spacings are not done in this study, because it is generally accepted that quantitative evaluation on da/dN versus striation spacing can be valid only in the region of $da/dN > 10^{-4}$ mm/c and most of the results in this study are concentrated on the region of $da/dN < 10^{-4}$ mm/c.

Up to now, important factors from a fractographical point of view are not revealed yet with which the difference of the crack growth behavior under both load conditions can be explained, but it is suggested, referring to several studies on impact fatigue, that the size of plastic deformed zone near the crack tip is one major factor. Such a conception is supported by the following experimental results; for example, the plastic deformed layer just beneath the crack growth surface is shallower in impact fatigue, the number of grains near the crack tip in which the slip bands are observed are few, and the near crack tip plastic deformation in the thickness direction is smaller than in non-impact fatigue¹¹. However, to evaluate the size of plastic zone quantitatively and

to investigate the relation between crack growth rate and plastic zone which is out of the scope of this study, the authors will investigate this subject in near future.

4. Conclusions

Impact fatigue crack growth tests under stress ratios of $R=0$ and -1 were carried out by using 2017-T3 aluminum alloy as experimental material, and the results obtained were discussed in comparison with those obtained in non-impact fatigue. Major conclusions obtained in this study are summarized as follows:

- (1) When the crack growth rates da/dN under both load conditions are plotted against maximum stress intensity factor K_{max} , the value of da/dN is higher in impact fatigue than in non-impact fatigue for both stress ratios of $R=0$ and -1 . Besides, the effect of compressive stress on da/dN in impact fatigue is less than in non-impact fatigue.
- (2) Next, when da/dN is rearranged against effective stress intensity factor range ΔK_{eff} , $da/dN-\Delta K_{eff}$ relations under impact fatigue do not show any dependence on stress ratios, and converge well to a straight line. Furthermore, the scatter of data depending on applied stress range becomes very small contrary to the representation on $da/dN-K_{max}$ diagram. These facts show that the arrangement with ΔK_{eff} is very effective. However, the difference of $da/dN-\Delta K_{eff}$ relations from those under non-impact fatigue still remains, and results in impact fatigue show higher value of da/dN than those in non-impact fatigue. Including the conclusion mentioned in (1), these characteristics of impact fatigue crack growth behaviors are the same as those observed with low carbon steel in previous study.
- (3) In the fracture surface observation, any notable difference in morphological

Fig.12 Examples of striation pattern under both stress conditions

Fig.13 Examples of intergranular facet under both stress conditions

patterns was not found between fracture surfaces under both load conditions, and so it was difficult from this point of view to explain the difference of crack growth rate under both load conditions in the range of this experiment.

As to above-mentioned characteristics of impact fatigue crack growth behavior, the authors would like to discuss the problem especially from a view point of quantitative evaluation of crack tip plastic deformed zone in near future.

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References

- (1) Nakayama, H., et al., Bull. of JSME, Vol.26, No.219 (1983-9), p1453.

- (2) Nakayama, H., et al., Bull. of JSME, Vol.27, No.227 (1984)
- (3) Iguchi, H., et al., Fatigue of Engng. Mat. Struc., Vol.2 (1979), p.165.
- (4) Murakami, R. and Akizono, K., Jour. Japan Soc. Str.Fract.Mat. (in Japanese) Vol.16, No.2 (1981-7), p.47.
- (5) Murakami, R. and Akizono, K., Jour. Japan Soc. Mat. Sci. (in Japanese) Vol.31, No.346 (1982), p.54.
- (6) Tanaka, T. and Nakayama, H., Bull. of JSME, Vol.16, No.12 (1973-12), p.1814.
- (7) Tada, H., Engng. Fra. Mech., Vol.3 (1971), p.345.
- (8) Kishimoto, K., et al., Jour. Japan Soc. Mat. Sci., (in Japanese), Vol.31, No.344 (1982), p.60.
- (9) Naito, Y. and Okamura, H., Trans. Japan Soc. Mech. Engrs., (in Japanese) Vol.43, No.366 (1977), p.407.
- (10) For instance, Subcommittee of Fractography in JSME, Jour. Japan Soc. Mech. Engrs., (in Japanese), Vol.76, No.658 (1973-9), p.1203.
- (11) Tanaka, T., et al., Preprint of Japan Soc. Mech. Engrs. (in Japanese), No.820-12 (1982-10), p.272.