Effects of Stress Wave Form and Superposition of Vibratory Stresses

on Cyclic SCC Crack Growth Behavior in an Al-Alloy*

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Influences of stress wave forms and superposition of vibratory stresses at the periods of the maximum stress under a low-frequency varying load on cyclic SCC have been investigated with a high-strength aluminum alloy, and the loading condition dominating over cyclic SCC and the competition between cyclic and dynamic SCC have been discussed. The threshold stress intensity factor for cyclic SCC, $K_{I\text{SCC}} = K_{I\text{FSCC}}$, is independent of hold time at the maximum stress, but increases with a decrease in varying load rates per time $\dot{K}$. At higher ΔK_{eff} , however, da/dN is enhanced with a decrease in ΔK_{eff} i.e., at longer rise time; this is similar to those of conventional corrosion fatigue. On the other hand, the superposition of vibratory stresses promotes corrosion products-induced wedge effects with $K_{\text{op}} = K_{\text{max}}$. In this case, K_{FSCC} is determined by the threshold stress intensity factor, K_{DSCC} , for dynamic SCC under the secondary vibratory stress condition.

Key words: Fatigue, Cyclic SCC, Dynamic SCC, Stress Wave Form, Superposition of Vibratory Stresses, Crack Growth, Threshold Values, Aluminum Alloy

1. Introduction

High-strength materials have come into wide use with industrial developments. However, high-strength materials are sensitive to environments and their environmental strengths including stress corrosion cracking (SCC) pose serious problems^{(1),(2)}. For the materials sensitive to SCC, we have emphasized the importance of dynamic loads⁽³⁾⁻⁽⁷⁾ such as small vibratory loads superimposed on a sustained load and low-frequency varying loads; the former causes dynamic SCC^{(3),(4)}, resulting in a lower threshold stress intensity factor $K_{I\text{max}} = K_{\text{DSCC}}$ than the one of static SCC $K_{\text{I SCC}}$; the latter causes cyclic SCC even at lower values than $K_{\text{I SCC}}$ ⁽⁵⁾⁻⁽⁷⁾. In a similar way to corrosion fatigue⁽⁸⁾⁻⁽¹³⁾, cyclic SCC crack growth behavior has been reported to be affected by the stress wave forms^{(5),(9),(14),(15)}. However, investigations were mainly focused on the region of higher crack growth rates, i.e., $K_{\text{max}} > K_{\text{I SCC}}$, and the wave form effects on cyclic SCC thresholds, K_{FSCC} , have been scarcely reported.

Moreover, machines and structures are frequently subjected to a low frequency varying trapezoidal stress with high frequency vibratory stresses of small amplitude superimposed. Endo et al.⁽¹⁶⁾ reported that superimposed waves at a low frequency of 0.67 Hz reduced crack growth rates for a high-strength aluminum alloy sensitive to active path corrosion (APC) type SCC because of crack blunting. However, in the case of the superposition of high frequency vibra-

tory stresses, under which dynamic SCC is dominant⁽¹⁷⁾, the competition of cyclic SCC and dynamic SCC poses serious problems; the former is owing to the primary low frequency varying load and the latter to the secondary high frequency vibratory loads.

In this investigation, the influences of stress wave forms and the superposition of high frequency vibratory stresses are investigated. Attention is paid to cyclic SCC thresholds, K_{FSCC} . And the mechanisms of cyclic and dynamic SCC are discussed in order to obtain design information to use high-strength materials.

2. Experimental procedures

The material tested was a high-strength aluminum alloy ZK141 (JIS 7N01), whose chemical composition, heat treatments, and mechanical properties are listed in Tables 1 through 3. Pin-loaded wedge opening loading (WOL) specimens with side grooves shown in Fig.1 were used, where crack plane orientation was T-L. Specimens were finally finished with diamond paste of 1 μm after polishing with #2000 emery papers. A corrosive environment, i.e., 3.5% NaCl solution prepared with reagent grade NaCl and deionized water (specific electric resistance $> 1 \text{ M}\Omega \cdot \text{cm}$), was circulated. The temperature of the solution was kept at $298 \pm 0.5 \text{ K}$ by a thermoregulator. In the corrosive solution, both sides of a specimen were coated with transparent silicone resin to prevent the specimen surfaces from corrosion damage in order to observe crack lengths.

Cyclic loading tests were carried out

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Table 1. Chemical composition of ZK141 alloy, mass percent.

Cu	Fe	Si	Mn	Mg	Zn	Cr	Ti	Zr	Al
0.14	0.19	0.06	0.34	1.7	4.4	0.17	0.04	0.16	R

Table 2. Sensitization heat treatments of ZK141 alloy.

Solution Heat Treatments	Quenching	Aging
833 K, 86.4 ksec F.C. 723 K	273 K, Water	343 K, 172.8 ksec

Table 3. Mechanical properties of ZK141 alloy.

0.2% Offset Yield Strength	Tensile Strength	Elongation
316 MPa	416 MPa	18%

Fig. 1. Shape and dimensions of test specimens. All dimensions are in mm.

by a 98 kN electrohydraulic fatigue testing machine. The stress wave forms generated by a micro-computer-aided programmable function generator are shown in Fig. 2: (a) a positive saw tooth wave, (b) a negative saw tooth wave, (c) a positive pulse wave, and (d) a negative pulse wave were applied to specimens at a stress ratio $R = K_{min}/K_{max}$ of 0.1 and a stress cycle frequency f of 0.1 Hz. In the case of a positive saw tooth wave, experiments were also conducted at $f = 0.01$ Hz. Moreover, the superimposed waves shown in Fig. 2(e) were used, where sinusoidal loads at a high frequency of 30 Hz were superimposed for 7.8 s (234 cycles) at the periods of the maximum load of the negative pulse wave, i.e., a primary wave. Stress ratios of secondary loads were 0.95 and 0.90. In the following sections, these superimposed waves will be called as follows: $R=0.95$ superimposed wave and $R=0.9$ superimposed wave, respectively.

Crack lengths were measured by a compliance technique and optical traveling microscopes whose minimum scales were 10 μm . Crack opening and closing points were measured by the unloading elastic compliance technique⁽¹⁸⁾; a MELCOM 70/10 minicomputer was interfaced to the fatigue testing machine, and crack opening and closing loads were automatically obtained by averaging a specific number of stress cycles (2-15 cycles) in order to improve accuracy. Stress wave forms and stress cycle frequencies were not changed during the measurements. As for superimposed waves, crack opening and clos-

(a) Positive saw tooth wave

(b) Negative saw tooth wave

(c) Positive pulse wave

(d) Negative pulse wave

(e) Superimposed wave

Fig. 2. Stress wave forms applied to specimens.

ing points of the primary loads were measured.

3. Experimental results and discussions

3.1. Relation between da/dN and ΔK

Figure 3 shows the relation between crack growth rates da/dN and stress intensity factor ranges ΔK in various stress waves. Results of fatigue in dry air at $R = 0.1$ and in 3.5% NaCl solution at $R = 0.1$ and $f = 30 \text{ Hz}$ ⁽¹⁷⁾ are also shown by the solid and the dotted lines in the figure, respectively.

At low ΔK , da/dN in 3.5% NaCl solution was lower than that in dry air except the positive pulse wave. Above a certain ΔK , however, a sudden enhancement of da/dN from that in dry air was observed; this abrupt crack growth enhancement is characteristic of cyclic SCC as has been reported elsewhere^{(5)-(7),(17)}. This crack growth enhancement was caused by rapid intergranular dissolution and subsequent transgranular hydrogen embrittlement, since K_{max} approached the threshold stress intensity factor for cyclic SCC, K_{FSCC} .

At $f = 0.1 \text{ Hz}$, ΔK_{FSCC} for the positive pulse wave was equal to the one for the negative pulse wave, and they had the smallest values. ΔK_{FSCC} increased in the order, the positive saw tooth wave and the negative saw tooth wave. On one hand, ΔK_{FSCC} for the positive saw tooth wave at $f = 0.01 \text{ Hz}$ was higher than that for the same wave form at $f = 0.1 \text{ Hz}$, and went up to the similar threshold value as the one for the negative saw tooth wave at $f = 0.1 \text{ Hz}$.

At higher ΔK (i.e., $\Delta K > 20 \text{ MPa m}^{1/2}$), da/dN for various waves at $f = 0.1 \text{ Hz}$ fell into a narrow scatter band. However, one may state that da/dN for the positive saw tooth wave at $f = 0.01 \text{ Hz}$ was higher than those for other waves at $\Delta K \geq 30 \text{ MPa m}^{1/2}$.

Fig.3. da/dN for various waves as a function of ΔK .

Figure 4 shows da/dN for the superimposed waves as a function of ΔK . Here, da/dN and ΔK are in terms of the primary waves. da/dN for the positive and the negative pulse waves were also taken from Fig.3. ΔK_{FSCC} for the $R=0.95$ superimposed wave increased from the one for the negative pulse wave. However, an increase of ΔK_{FSCC} from the one for the negative pulse wave became smaller, as the superimposed stress amplitude increased (i.e., $R=0.9$ superimposed wave).

At higher ΔK , da/dN for the $R=0.9$ superimposed wave was higher than those for the positive and the negative pulse waves. But da/dN for the $R=0.95$ superimposed wave was smaller than those for the positive and the negative pulse waves.

3.2. Crack opening and closing behavior

Figure 5 illustrates the relation between crack opening stress intensity factors, K_{op} , and maximum stress intensity factors, K_{max} . In this investigation, crack opening loads were equal to crack closing loads, and no differences were observed between load-displacement curves at loading and unloading periods, which were reported for type 410 stainless steel in 1% NaCl solution at high frequencies⁽¹⁹⁾.

In a low K_{max} region, K_{op} in 3.5% NaCl solution was higher than that in dry air, and its increase was remarkable especially for the positive saw tooth wave at a lower frequency of 0.01 Hz. This increase in K_{op} was brought about by the corrosion products-induced wedge effects^{(17),(19),(20)}, which was supported by the fact that the fracture surfaces were covered with thick layers of corrosion products. A further increase in K_{op} for the positive saw tooth wave at $f = 0.01 \text{ Hz}$ than other waves was caused by an increase in the amount of corrosion products within the crack associated with an increase

Fig.4. da/dN for superimposed waves as a function of ΔK .

Fig. 5. K_{op} as a function of K_{max} .

in exposure time of the crack tip to the corrosive environment.

On one hand, K_{op} for the superimposed waves was equal to K_{max} at low K_{max} ; K_{op} was the highest in the various waves examined. This increase in K_{op} was brought about by the superimposed waves promoting the dissolution behind the crack tip and a remarkable increase in corrosion products within the crack occurred. With increasing K_{max} (ΔK), a sudden enhancement of da/dN for the superimposed waves occurred, leading to a relative decrease in corrosion products producing rates; K_{op} values fell off, and became closer to the values of other waves.

3.3. Relation between da/dN and ΔK_{eff}

Figure 6 shows the relation between da/dN and effective stress intensity factor ranges, ΔK_{eff} . Irrespective of wave forms, da/dN at $f = 0.1$ Hz scattered at low ΔK_{eff} , and fell into the shaded band in the figure: da/dN was independent of wave forms at low ΔK_{eff} . However, da/dN at $f = 0.01$ Hz for the positive saw tooth wave was higher than that at $f = 0.1$ Hz.

At high ΔK_{eff} , on the other hand, the dependence of da/dN on wave forms became more evident than that in terms of ΔK : da/dN for the positive saw tooth wave at $f = 0.01$ Hz was the highest, and then came in the order, the positive saw tooth wave at $f = 0.1$ Hz, the negative saw tooth wave, and the positive and the negative pulse waves.

Figure 7 illustrates da/dN for the superimposed waves as a function of ΔK_{eff} . The shaded zone in the figure represents the scatter band of da/dN at $f = 0.1$ Hz in Fig. 6.

At low ΔK_{eff} , da/dN for the superimposed waves increased from the scatter band at $f = 0.1$ Hz, and the enhancement was especially remarkable in the $R=0.9$ superimposed wave. For the $R=0.9$ superimposed wave, an increase in da/dN continued to higher ΔK_{eff} . This crack growth enhancement was produced by superposition of dynamic SCC, which was caused by the superimposed vibratory stresses; passive films formed at the crack tips were ruptured by the superimposed vibratory stresses, resulting in the promotion of intergranular dissolution and subsequent transgranular hydrogen embrittlement. For the $R=0.95$ superimposed wave at high ΔK_{eff} , on the other hand, the

Fig. 6. da/dN for various waves as a function of ΔK_{eff} . Fig. 7. da/dN for superimposed waves as a function of ΔK_{eff} .

influences of small vibratory stresses on da/dN were not observed. The values of da/dN were equal to those for the positive and the negative pulse waves.

3.4. Fracture surface morphology

The fracture surface, near which an increase in K_{op} was observed, was covered with thick layers of corrosion products as was observed in the same material⁽¹⁷⁾. This thick layer of corrosion products indicates that the corrosion products-induced wedge

effects occurred effectively. But the fracture surface, near which an abrupt enhancement of crack growth was observed, exhibited inter- and transgranular crackings⁽¹⁷⁾.

Figures 8 through 10 show the fracture surfaces at high ΔK_{eff} ($\Delta K_{eff} \approx 20 \text{ MPa m}^{1/2}$). In the case of longer rise time (see Figs. 8 and 9), the fracture surfaces exhibited inter- and transgranular crackings. Especially at $f = 0.01 \text{ Hz}$ (Fig. 8), the transgranular cracking portions suffered dissolution in spite of higher ΔK_{eff} (i.e., higher da/dN). In the case of rapid rise time (Fig. 10) transgranular cracking characterized by brittle striations shown in Fig. 10(b) was dominant, and intergranular cracking was hardly observed.

In the case of the $R=0.9$ superimposed wave, inter- and transgranular crackings were observed. Figure 11 shows the fracture surfaces of the $R=0.9$ superimposed wave. In some intergranular portions intergranular striations whose spacings were almost equal to macroscopic crack growth rates for a primary wave were observed. Stereographical observations verified that these striations

were very flat and were different from fatigue striations in shape. The intergranular striations would be formed by the unloading of the primary load: it led to a crack closure, and anodic dissolution at grain boundaries was prevented. Brittle transgranular striations were also observed as shown in Fig. 11(b). The microscopic crack growth direction in the brittle transgranular striations made an angle of 50-70 degrees to the macroscopic crack growth one shown by the arrow. This implies that first occurred intergranular dissolution and then came brittle transgranular striations due to hydrogen embrittlement.

Fracture surfaces were classified into five types including 1) intergranular cracking (IG), 2) brittle transgranular cracking (BTG), 3) ductile transgranular cracking (DTG), 4) dimples (D), and 5) fracture surfaces which were difficult to be classified because of corrosion products (MISC). Figure 12 shows the relation between fracture area fractions and ΔK_{eff} . In the figure, "s" is affixed to data when brittle transgranular striations were observed, and

Fig. 8. Fracture surface; positive saw tooth wave, $R = 0.1$, $f = 0.01 \text{ Hz}$, $K_{max} = 34.1 \text{ MPa m}^{1/2}$, $\Delta K_{eff} = 21.3 \text{ MPa m}^{1/2}$. Arrow shows direction of crack growth.

Fig. 9. Fracture surface; positive saw tooth wave, $R = 0.1$, $f = 0.1 \text{ Hz}$, $K_{max} = 32.4 \text{ MPa m}^{1/2}$, $\Delta K_{eff} = 20.6 \text{ MPa m}^{1/2}$. Arrow shows direction of crack growth.

(a) Low magnification photograph.

(b) Details of (a); brittle transgranular striations.

Fig. 10. Fracture surfaces; negative saw tooth wave, $R = 0.1$, $f = 0.1 \text{ Hz}$, $K_{max} = 31.0 \text{ MPa m}^{1/2}$, $\Delta K_{eff} = 19.1 \text{ MPa m}^{1/2}$, $da/dN \sim 6.6 \times 10^{-6} \text{ m/c}$. Arrow shows direction of crack growth.

"*" is when intergranular striations were observed.

At low ΔK_{eff} , fracture surfaces were covered with intergranular and brittle transgranular crackings irrespective of stress wave forms including the superimposed waves. At high ΔK_{eff} with shorter rise time, brittle transgranular cracking with brittle striations was dominant. At high ΔK_{eff} with longer rise time, however, intergranular and brittle transgranular crackings were dominant in a similar way to those at lower ΔK_{eff} .

For the $R=0.95$ superimposed wave at higher ΔK_{eff} , brittle transgranular cracking was dominant and its fracture surface morphology was similar to those for the positive and the negative pulse waves. This agreed with the fact that the effects of small vibratory stresses on da/dN for the $R=0.95$ superimposed wave were negligible. For the $R=0.9$ superimposed wave, however, intergranular and brittle transgranular crackings were still dominant even in the high ΔK_{eff} region, at which da/dN increased

(a) Intergranular striations.

Intergranular striation → Brittle transgranular striation

(b) Intergranular and brittle transgranular striations.

Fig.11. Fracture surfaces; $R=0.9$ superimposed wave, $K_{max} = 23.4$ MPa $m^{1/2}$, $\Delta K_{eff} = 10.3$ MPa $m^{1/2}$, $da/dN \sim 3.4 \times 10^{-6}$ m/c. Arrow shows direction of crack growth.

from those for the positive and the negative pulse waves on account of the superposition of vibratory stresses. Moreover intergranular striations existed; this indicates that anodic dissolution was more enhanced.

3.5. Wave form effects on K_{FSCC}

Figure 13 shows K_{FSCC} for various wave forms as a function of stress intensity factor rates, $K = |dK/dt|$, at both loading and unloading. Short lines (|) are added to the plots in the case of unloading. K_{FSCC} values for the triangular wave at $R = 0.1$ and $f = 0.1$ Hz and for the sinusoidal wave at $R = 0.1$ and $f = 30$ Hz⁽¹⁷⁾ are also shown in the figure. K values for the superimposed waves were calculated on the primary loads.

As is mentioned before, K_{FSCC} for the negative pulse wave was equal to that for the positive pulse wave, and the influence of hold time on K_{FSCC} was not observed. This indicates that passive films at the crack tip, which had been ruptured by the primary load, were restored within successive short hold time (< 1.35 s). This would mean no influence of hold time at the maximum stress on K_{FSCC} .

From the figure, one can conclude that K_{FSCC} increased with decreasing K . In this material/environment system, repassivation rates were very fast as was indicated by no influence of hold time at the maximum stress on K_{FSCC} and da/dN . Therefore, the restoration of passive films predominated at lower K , i.e., positive saw tooth waves, resulting in higher K_{FSCC} with respect to that at higher K , i.e., pulse waves. Many investigators^{(8),(10)-(13)} emphasized that crack growth rates in conventional corrosion fatigue increased with decreasing K (i.e.,

Fig.12. Effects of stress wave forms on fracture area fractions.

Fig. 13. K_{FSCC} as a function of K .

longer rise time). One should note that the dependence of cyclic SCC thresholds on K is strongly contrastive to that of corrosion fatigue. Moreover K_{FSCC} for the negative saw tooth wave was almost equal to that for the positive saw tooth wave at $f = 0.01$ Hz, and had a greater K_{FSCC} value compared at a given K . In conventional corrosion fatigue, longer fall time (i.e., longer stress decreasing time), longer hold time at the maximum stress^{(9),(12)}, and longer hold time at the minimum stress were reported to reduce da/dN ^{(9),(13)}. In cyclic SCC, longer fall time would similarly reduce da/dN values at lower ΔK_{eff} .

For the superimposed waves, K_{FSCC} increased with respect to those for the positive and the negative pulse waves in spite of having the similar K values. This increase of K_{FSCC} was especially remarkable for the $R=0.95$ superimposed wave. Then da/dN values for the superimposed waves were converted into crack growth rates, da/dt , as is shown in Fig. 14. The figure also shows da/dt for dynamic SCC at $R = 0.95$ and 0.9 ($f = 30$ Hz), and that for static SCC⁽³⁾.

K_{FSCC} for the $R=0.95$ superimposed wave was equal to K_{DSCC} at $R = 0.95$, and similarly K_{FSCC} for the $R=0.9$ superimposed wave was to K_{DSCC} at $R = 0.9$. As is shown in Fig. 5, K_{op} for the superimposed waves increased ($K_{op} = K_{max}$), and therefore, the primary varying loads could not bring about active slip steps effectively. This led to higher K_{FSCC} values for the superimposed waves than those for pulse waves. In this situation an abrupt crack growth enhancement from that in dry air never occurred until K_{max} approached the dynamic SCC threshold values, above which the secondary vibratory stresses caused dynamic SCC crack growth. Namely, K_{FSCC} values for the superimposed waves were determined by K_{DSCC} values under the secondary vibratory stress conditions.

3.6. Wave form effects on da/dN at high ΔK_{eff}

Figure 15 illustrates the relation between da/dN and effective stress intensity factor rates at loading, ΔK_{eff} , at a high ΔK_{eff} of $20 \text{ MPa m}^{1/2}$.

At high ΔK_{eff} , da/dN increased with decreasing ΔK_{eff} , i.e., longer rise time, in a similar way to those reported for conven-

Fig. 14. da/dt for superimposed waves as a function of K_{max} . Fig. 15. da/dN as a function of ΔK_{eff} ; $\Delta K_{eff} = 20 \text{ MPa m}^{1/2}$.

tional corrosion fatigue. This dependence of da/dN on ΔK_{eff} was contrastive to that of K_{FSCC} , which was supported by the fractographical observations: in the case of longer rise time (i.e., lower ΔK_{eff}) the percentage of intergranular cracking was larger than that at shorter rise time, and the crack growth was promoted by intergranular dissolution and successive transgranular hydrogen embrittlement in a ligament zone. Moreover, even if the importance of hold time at the maximum stress was pointed out at $K_{max} > K_{ISCC}$ ^{(5),(14),(15)}, the influence of hold time on da/dN was not observed as those in K_{FSCC} . This implies that da/dN was controlled by rise time, not by hold time. This was further supported by the fracture surface morphology; brittle transgranular cracking with brittle striations was dominant irrespective of hold time (see Fig. 12).

On one hand, da/dN for the $R=0.95$ superimposed wave was almost equal to that for the negative pulse wave, but da/dN for the $R=0.9$ superimposed wave increased to the identical values of dynamic SCC at $R = 0.9$. In other words, da/dN for the $R = 0.95$ superimposed wave was controlled by the primary load, and the fracture surface was similar to that for the negative pulse wave: brittle transgranular cracking was dominant. However, with widening the superimposed vibratory stress range, i.e., in the case of the $R=0.9$ superimposed wave, an enhancement of da/dN was caused by dynamic SCC, and a mixed mode of intergranular and brittle transgranular cracking which was similar to that for dynamic SCC⁽³⁾ appeared.

4. Conclusions

The effects of stress wave forms including the superposition of vibratory stresses, have been investigated with a high-strength aluminum alloy ZK141 (JIS 7N01) sensitive to APC type SCC. The following have been made clear:

(1) da/dN near K_{FSCC} for ZK141 alloy in a corrosive environment decreases from that in dry air in terms of ΔK , which is caused by the corrosion products-induced wedge effects. At higher ΔK above K_{FSCC} , however, da/dN increases from dry air values.

(2) K_{FSCC} for ZK141 alloy is independent of hold time. However, K_{FSCC} increases with decreasing K , because the restoration of passive films becomes more predominant with decreasing K .

(3) When considered in terms of ΔK_{eff} which eliminates the wedge effects, deceleration of da/dN from dry air at low ΔK values vanishes. da/dN at low ΔK_{eff} is independent of stress wave forms at $f = 0.1$ Hz. But da/dN for the positive saw tooth wave at $f = 0.01$ Hz increases from those for other waves at $f = 0.1$ Hz. At high ΔK_{eff} , on the other hand, the dependence of da/dN on stress wave forms is clearer than in terms of ΔK : da/dN increases with increasing rise time.

(4) A superposition of vibratory stresses on the negative pulse wave promotes the corrosion products-induced wedge effects, leading to $K_{op} = K_{max}$. In this case, the K_{FSCC} values are determined by the K_{DSCC} values under the secondary vibratory stress conditions with higher K_{FSCC} values than those for the negative pulse wave.

(5) In terms of ΔK_{eff} , da/dN for the superimposed waves is enhanced owing to dynamic SCC, which is brought about by the secondary vibratory stresses; an enhancement of da/dN is especially remarkable for the $R=0.9$ superimposed wave.

(6) The fracture surfaces of ZK141 alloy, where a crack growth deceleration is observed, are covered with thick layers of corrosion products. This is indicative of the corrosion products-induced wedge effects. At $K_{max} > K_{FSCC}$, a mixed mode of intergranular and brittle transgranular cracking is observed. At higher ΔK_{eff} with longer rise time, a mixed mode of fracture surfaces is also dominant. However, at higher ΔK_{eff} with shorter rise time, a brittle transgranular failure characterized

by brittle striations is dominant. As for the $R=0.95$ superimposed wave, the fracture surfaces are covered with a brittle transgranular failure with brittle striations, whose features are the same as those with shorter rise time. However, the fracture surface for the $R=0.9$ superimposed wave exhibits a mixed mode of intergranular (with intergranular striations) and transgranular (with brittle striations) failures.

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