Study on Crack Growth Behavior in Impact Fatigue*

(Part 1, Impact Fatigue Crack Growth Characteristics of
0.1%C Aluminum Killed Steel)

By

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A series of experiments are conducted to investigate the impact fatigue crack growth behavior of 0.1%C aluminum killed carbon steel conforming to JIS. S10C. And results obtained are discussed from several viewpoints in comparison with those in non impact fatigue.

It is clear that macroscopic crack growth rate, da/dN , in impact fatigue is higher than that in non impact fatigue especially in relatively low K_{max} or low ΔK region. Through quantitative analysis of fracture surface morphology, it is revealed that the higher crack growth rate in impact fatigue is sustained by the larger amount of intergranular fracture mode which accelerates crack growth rate to some extent.

Other characteristical aspects in impact fatigue crack growth behavior are also described in detail.

Key Words: Impact Fatigue Load, Fatigue Crack Growth Rate, Stress Range Dependence, Morphologic Analysis of Fracture Surface, Striation Pattern

1. Introduction

In the studies on impact fatigue behavior of metallic materials done by the authors especially from a viewpoint of design engineering¹⁻¹⁰, it was revealed that there did exist the impact fatigue characteristics composed of two aspects, i.e., the lower fatigue strength under impact loading cycles and the localization of inelastic strain behavior in impact fatigue¹¹.

The literatures¹²⁻¹⁷ support the impact fatigue strength characteristic mentioned above, but there exist a few experimental results which show somewhat different strength trends depending on experimental conditions¹⁷⁻²⁰. The inelastic strain behavior characteristic is also sustained by more concrete evidence, e.g., the stronger dependence on crystal grains for slip bands generation under impact fatigue compared with the slip bands formation under non impact fatigue¹⁷.

Recently, considerable attention has been paid to impact fatigue crack growth behavior. And experimental data on fatigue crack growth rate and topographic feature of fatigue fracture surface are now accumulating positively^{8-10, 17, 18, 21-29}.

However, any valid concept to evaluate the characteristics observed in impact fatigue crack growth behavior, e.g. high growth rate in impact fatigue, has not been established yet.

As part of the authors ongoing program to obtain systematic knowledge on impact fatigue crack growth behavior, a series of experiments are conducted by using 0.1%C aluminum killed steel as an experimental material. Characteristics of impact fatigue crack growth behavior revealed on da/dN - K_{max} and ΔK relations are discussed in detail in comparison with results in non impact fatigue, and it is tried to explain them through topographical analysis of fatigue fracture surface observed with SEM.

2. Experimental Material and Specimen

0.1%C aluminum killed steel conforming to the JIS.S10C used in this study was supplied as hot rolled bars of 25mm in diameter. The chemical composition in wt. percent, and the condition of heat treatment and mechanical properties in static tension test are listed in Table 1 and Table 2 respectively. About 3mm thick plates obtained by cold rolling of several steps were machine-finished to shape and sizes of a center-notched specimen indicated in Fig.1 after the heat treatment. The average grain size of the material after the heat treatment is about 50 μ m. As is shown in Fig.1, both sides of a drilled hole of 1mm in diameter were saw-cut to obtain a crack starter notch of about 1.8mm in total length. and both faces of the specimen were electro-polished by about 20 μ m to remove the machining affected layer. Then, to facilitate crack length observation with a travelling microscope, the specimen surface to be observed was polished lightly with emery paper of high grade perpendicularly to the

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Table 1 Chemical composition of the material

Material	Chemical composition (%)						
	C	Si	Mn	P	S	Sol.AL	Total N
CH10A	0.097	0.009	0.47	0.011	0.017	0.028	0.0042

Table 2 Condition of heat treatment and mechanical properties

Heat treatment	Upper yield stress σ_{so} (MPa)	Lower yield stress σ_{su} (MPa)	Ultimate tensile strength σ_B (MPa)	Breaking strength on final area σ_T (MPa)	Elongation δ (%)	Reduction of area ϕ (%)
920°C, 1h, F.C. 350°C, 1h, F.C.	193	177	335	723	46.4	68.0

Fig.1 Shape and sizes of the specimen

crack propagating direction.

3. Experimental Apparatus and Procedure

Principle of an impact fatigue testing machine used in this experiment is shown in Fig.2. The machine was designed and manufactured by way of trial by A. Chatani¹².

Mechanism to generate impact load is as follows; a steel pipe of 600mm in length collides with a stopper fixed at the left side end of a steel rod in a crank-slider mechanism, and the impact tensile load produced by the collision is transmitted to a specimen fixed between the right side end of the steel rod and a block. Magnitude of the impact load is adjusted by changing the collision velocity of the steel pipe with the stopper, and this adjustment is attained by changing the eccentricity of the crank device. Besides, a cyclic frequency of this testing machine is about 9Hz. Non impact fatigue tests were conducted on 30KN electro servohydraulic fatigue testing machine, operating under load control at cyclic frequency of 10 or 30Hz (sine wave).

The impact fatigue testing machine shown

in Fig.2 is not equipped with a load cell to detect both the magnitude and the shape of the impact stress wave in its load train, so the stress on the specimen is determined by the amplified output voltage of a wheat-stone bridge connected by using four strain gages cemented near side edges on both faces of the specimen as active gages, where the calibration relation between the stress and the output voltage is obtained beforehand in a static tension test of low load for each specimen. Location where strain gages were cemented is represented in Fig.3.

An example of the impact stress pattern obtained is shown in Fig.4. As is shown in this figure, the impact stress in this experiment is composed of the initial tensile impact stress with high rise time of about 0.3ms and the subsequent compressive stress and then the decaying stress vibration of relatively small amplitude. Here, only the maximum tensile stress σ_{tmax} and the maximum compressive stress σ_{cmax} are used as parameters of the impact stress in evaluating the crack growth behavior. Besides, stress range $\Delta\sigma(=\sigma_{tmax} - \sigma_{cmax})$ showed a trend to increase slightly during

Fig.2 Principle of the impact fatigue testing machine

Fig.3 Strain gages for stress measurement

Fig.4 An example of the impact stress pattern

the impact fatigue test, so the stress values of $\sigma_{\max}$ and $\sigma_{\min}$ are determined as the mean values of these stresses obtained by measurement done at regular intervals during tests. Such a treatment of stress values does not affect the valid evaluation of the experimental results as is described in the following chapter.

Prior to the experiments, fatigue-precracks were introduced under fully reversed push-pull load cycles for all specimens, where stress amplitude for fatigue-precracking was determined not to exceed the maximum tensile stress $\sigma_{\max}$ in non impact and impact fatigue tests. As the stress range $\Delta\sigma$ was maintained constant throughout the experiments, the fatigue crack growth in this study is that under K-increasing condition.

4. Experimental Results and Discussions

4-1. Fatigue crack growth behavior in impact fatigue

In this section, whole feature of the impact fatigue crack growth behavior is discussed in comparison with results in non impact fatigue.

At first, da/dN - ΔK relations in non impact fatigue under the stress ratios of -1 and -0.4 are shown in Fig.5, where stress ratio means the ratio of the minimum stress to the maximum stress. And the scattering band for da/dN - ΔK_{eff} ($=U\Delta K$) relation is also shown in Fig.5 for both stress ratios, where U is the effective stress range ratio obtained experimentally. Furthermore, da/dN - ΔK relation for stress ratio $R=-0.6$ is interpolated from the results under $R=-1.0$ and -0.4 by the method proposed by A. Ohta, et al.³⁰ and is shown as a solid line in Fig.5. The curve obtained for $R=-0.6$ is to be used as a fundamental curve to discuss the impact fatigue crack growth behavior, for the stress ratio of the impact stress obtained in this experiment is about -0.6 as a mean value as described below.

Stress intensity factor is calculated by the following formula proposed by H. Tada³¹.

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

$$\lambda = 2a/W$$

where a is half length of crack and W plate width. Though it is considered that elastic stress field around the crack tip under impact loading somewhat differs from that under non impact loading, Eq.(1) is adopted to determine the value of K regardless of the difference in the stress pattern. Such a treatment in this study is due to the lack of any general method for evaluating the K -value of several sorts of impact stress patterns obtained experimentally. Some problems involved with K -evaluation for impact stress are described briefly at the end of Section 4-2.

Secondly, impact fatigue crack growth rate is represented against the maximum stress intensity factor, $K_{\max}$ in Fig.6. As is shown in this figure, the stress ratio in impact fatigue scatters in the range of about $-0.5 < R < -0.7$, so the value of $R=-0.6$

Fig.5 Crack growth curve in non impact fatigue

Fig.6 Crack growth curve in impact fatigue

can be taken as an average value. Additionally, the estimated da/dN - $K_{\max}$ curve for non impact fatigue of $R=-0.6$ is also drawn in Fig.6 for the purpose of comparison. It is noted that the stress ratio shows a trend to take a greater value with an increase in the stress range $\Delta\sigma$. This trend comes from the mechanism of the impact fatigue testing machine. That is, when the collision velocity of the steel pipe with the stopper becomes higher the impact stress propagated to the specimen increases its magnitude. But the contribution of the collision speed is much more effective to the impact stress of tensile side but not so to the compressive side one.

From Fig.6, the following peculiarity of the impact fatigue crack growth rate can be observed: (1) da/dN - $K_{\max}$ relation in impact fatigue shows clear dependence on the stress range $\Delta\sigma$; in other words, the greater the value of $\Delta\sigma$ becomes, the higher da/dN

becomes in impact fatigue; (2) in relatively low K_{max} range, da/dN in impact fatigue is higher than that in non impact fatigue when comparison is done with the estimated curve for non impact fatigue of $R=-0.6$, but such a discrepancy diminishes gradually with an increase in K_{max} value, and in the range of $K_{max} > 15 \text{ MPa}/\sqrt{\text{m}}$ there does not exist any significant difference.

As described above, the impact fatigue crack growth curve can be classified into two regions: a region where the value of da/dN in impact fatigue is higher than that in non impact fatigue and da/dN relations under both of the stress conditions lie parallel with each other, and a region where the slope of da/dN - K_{max} relation in impact fatigue becomes moderate approaching asymptotically the relation in non impact. The impact fatigue crack growth in the former region seems to be attributed to the contribution of the accelerating factor to da/dN such as intergranular fracture mode³². On the other hand, as for the behavior in the latter region, it is assumed that the distinct influence of the accelerating factor diminishes and transgranular type of fracture such as striation mechanism becomes a predominant fracture mode the same as in non impact fatigue. Such a speculation will be discussed in the following section based on quantitative evaluation of topographical feature constituted on fracture surface.

In this experiment, evaluation of da/dN is restricted to the region below 10^{-4} mm/c due to the thickness and the width of the specimen used³³. And a macroscopic reduction of area is observed to occur, in non impact fatigue, over the K_{max} value of about $18 \text{ MPa}/\sqrt{\text{m}}$. It is well known that macroscopic crack growth rate da/dN is in poor agreement with striation spacing S but $S > da/dN$ in general in the range of $da/dN < 10^{-4} \text{ mm/c}$ ³⁴. So, values of the striation spacing observed clearly in impact fatigue in the range of $da/dN > 10^{-4} \text{ mm/c}$ are plotted against ΔK in Fig.7. This figure shows that the configuration of the impact fatigue crack growth behavior against the estimated curve for non impact fatigue well resembles that represented against K_{max} shown in Fig.6, and that the striation spacing in impact fatigue is well distributed around the extrapolated line of the estimated curve. It is considered as one of the impact fatigue crack growth characteristics that distinct striation patterns can be observed even at high ΔK region where the major fracture mode in non impact fatigue is dimple patterns.

Then, it is suggested from Fig.7 that crack closure behavior in impact fatigue differs considerably from that in non impact fatigue especially in relatively high ΔK region where da/dN - ΔK_{eff} relation in impact fatigue lies upon the band of da/dN - ΔK_{eff} relation in non impact fatigue when considered from the viewpoint that the effective stress intensity factor range ΔK_{eff} plays the role of a key parameter in crack growth rate³⁵. Though crack closure in impact fatigue had not been investigated in the present study because of a complexity of the impact stress pattern, crack closure

Fig.7 Correspondence of striation spacing S with da/dN in impact fatigue

behavior was observed under a simple stress pattern in a recent study by the authors and results of this study will be published in Trans. Japan Soc. Mech. Engrs. in near future³⁶.

Besides, solid circles (●) plotted in Fig.6 and 7 mean K_{max} and ΔK values calculated based on the real extremum values of the impact stress measured at initial and final stages of the experiment whose average $\Delta\sigma$ value is 213 MPa (○). Both of the results (● and ○) calculated based on the average and the real values of the impact stress are in close location with each other, so the evaluation based on the average $\Delta\sigma$ value does not give any influence on the discussions done above.

4-2. Fractographic features in impact fatigue

From Fig.8(a),(b) showing macroscopical views of fracture surfaces under both types of the stress conditions, peculiar fracture surface appearance in impact fatigue can be recognized. When K_{red} is defined as the value of K_{max} at which reduction of area occurs macroscopically, K_{red} of about $18.4 \text{ MPa}/\sqrt{\text{m}}$ is obtained for the results under non impact fatigue as an average value of the three specimens tested, and the corresponding net stress to the ligament onet is about 207 MPa which slightly exceeds the lower yield stress in static tension test. On the other hand, the reduction of area is not observed to occur in impact fatigue, when the stress range $\Delta\sigma$ is not so wide, almost up to final fracture stage, as is shown in Fig.8(b). Such a feature on fracture surface is not observed in non impact fatigue. However, fracture surfaces in impact fatigue under relatively high

Fig.8 Macroscopical view of fatigue fracture surface

stress range of $\Delta\sigma \geq 204\text{MPa}$ show the occurrence of reduction of area, but even in these cases K_{red} and σ_{net} take values of about $21.2\text{MPa}\sqrt{\text{m}}$ and 299MPa respectively which are much greater than those in non impact fatigue.

Here, it is valid to consider whether the reduction of area occurs or not depends on the relative magnitude of crack tip plastic zone size to the ligament size. So, it is suggested, from the comparison of the macroscopical views of the fractured surfaces under both types of stress conditions shown in Fig.8, that the plastic zone size in impact fatigue is smaller than that in non impact fatigue. Though experimental measurement on the plastic zone size was not made in this study, the experimental verification by H. Iguchi, et al. supports the assumption done above; they pointed out that the depth of the plastic deformed zone in a wake of the crack propagation was shallower in impact fatigue than in non impact fatigue from the aspect of half value breadth variation of X-ray diffraction profile¹⁷.

To evaluate the characteristic crack growth behavior in impact fatigue from the viewpoint of fractographic feature, detailed observations were done with SEM. Examinations are done, at first on the area fractions of intergranular facet and of transgranular cleavage facet to the reference area taken arbitrarily at several ΔK levels, and next on the whole feature of fracture surface topography. The area fractions of f_i and f_c are plotted against ΔK in Fig.9, where f_i and f_c are area fractions of intergranular facet and of transgranular cleavage facet discriminated clearly on fractographs. Additionally, results by C. Masuoka, et al.³⁷⁻⁴⁰ and T. Ishihara⁴¹ are also cited for the purpose of reference in Fig.9. It is seen from Fig.9 that the area fraction f_i in impact fatigue is greater than that in non impact fatigue in low ΔK region, and that the transgranular cleavage facet shows a trend to increase gradually with ΔK .

The higher crack growth rate in impact fatigue observed in this study can be attributed to the contribution of intergranular type of fracture mode, for the higher value of f_i in impact fatigue is observed in relatively low ΔK region where da/dN in impact fatigue is higher than that in non

Fig.9 Area fraction of f_i and f_c against ΔK

impact fatigue. However, the striation mechanism comes to play a major role also in the impact fatigue crack growth in the region where da/dN in impact fatigue shows a trend to approach that in non impact fatigue because the striation spacing S in impact fatigue in relatively high ΔK region well coincides with the extrapolated crack growth curve for non impact fatigue as is shown in Fig.7. And intergranular and transgranular cleavage types of fracture play only a supplemental role in crack growth rate of such a region.

Typical fractographs under both load conditions are shown in Fig. 10 and 11. Photo.(1) in each figure shows intergranular type of fracture. Especially under impact load condition, transgranular cleavage fracture as shown in Photos.(2) and (3) of Fig.11 is observed with the area fraction indicated in Fig.9, where Photo.(2) shows transgranular facet adjacent to striation pattern and Photo.(3) that over two crystal grain. Furthermore, it is concluded that the decaying stress vibration shown in Fig.3 does not influence the striation pattern, for a clear striation pattern in Fig.5(a) reflects the influence of extreme values of stress during cycle, i.e., σ_{max} and σ_{min} only. As the other investigators demonstrate that the striation pattern in impact

Fig.10 SEM-Fractographs in non impact fatigue

Fig.11 SEM-Fractographs in impact fatigue

fatigue is somewhat distinct relative to that in non impact fatigue^{17,18,25}, similar feature is observed also in this study when striation patterns under both load conditions shown in Figs.10 and 11 are compared with each other.

Up to the present, high impact fatigue crack growth rate has been discussed mainly from two different viewpoints: from the concept of dynamic stress intensity factor K_D which is greater than ordinary or static stress intensity factor^{24,27}, and from the topographical feature of fracture surface, i.e., from the theory that the large amount of intergranular and transgranular cleavage facet observed somewhat largely in impact fatigue would play as an accelerating factor

in da/dN ^{17,18}. Though the formally described dynamic stress intensity factor K_D is a numerically determined one under a strict step function type stress input⁴², impact stress patterns obtained experimentally possess a rise time of $10^{-10} \mu\text{s}$ order and furthermore the stress-time history in impact stress becomes dull just beneath its peak value. Thus the direct application of the K_D concept is questionable when there is a difference between the stress pattern used for calculating K_D value and that obtained experimentally²⁹. And such a question as above is also suggested from the discussions on dynamic stress concentration factor α_D ^{43,44}.

Consequently, it is necessary to develop

an all-embracing and careful evaluation of the impact fatigue crack growth characteristics based on experimental results obtained, for there exists, in impact fatigue, intrinsic peculiarity in crystallographic plastic deformation behavior which is different that under non impact fatigue, e.g., the problem on crystal grains selection concerning slip bands generation as was introduced in section 4-2.

5. Conclusions

As a first study in an ongoing program to investigate impact fatigue crack growth behavior, a series of fatigue crack growth tests are conducted by using 0.1%C aluminum killed steel as an experimental material. Characteristics in impact fatigue crack growth behavior are discussed from the viewpoints of da/dN - K_{max} , ΔK relation and fractographic feature in comparison with those in non impact fatigue.

Major conclusions obtained are as follows;

- (1) Crack growth rate in impact fatigue is higher than that in non impact fatigue especially in low growth rate region, and such a difference in crack growth rate disappears in high growth rate region due to asymptotical approach of da/dN in impact fatigue to that in non impact fatigue.
- (2) The impact fatigue crack growth curve shows a strong dependence on the experimental stress range; in other words, the greater the stress range becomes, the higher the crack growth rate becomes in impact fatigue.
- (3) Macroscopically, some of the fracture surfaces in impact fatigue are flat without reduction of area up to the final fracture stage, but not so in non impact fatigue. Such a feature is considered one of the characteristics in impact fatigue related with the crack tip plastic zone size in impact fatigue.
- (4) Distinct striation patterns are observed in impact fatigue in high stress intensity factor region where unstable crack growth occurs in non impact fatigue. And the striation spacing S in such a region well coincides with the extrapolated da/dN - ΔK curve for non impact fatigue.
- (5) High da/dN in impact fatigue is attributed to the higher occurrence ratio of intergranular type of fracture mode in the corresponding K region.

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