Growth of Crack in Steel by Impact Tension*

By Ichiro MAEKAWA**, Yuji TANABE***, Hisao WATANABE****,
Zhihao JIN⁺ and Yoshiki OGAWARA⁺⁺

This paper describes the critical crack growth condition of cracked steel specimens at 77 K under impact tension.

Impact tension was imposed on a specimen under a static tension σ_s . In the fracture tests, impact stress σ_d did not depend on σ_s for a lower range of σ_s but it decreased with an increase of σ_s for a higher range of σ_s . On the other hand, critical impact stress, σ_{cd} , to growth of a crack was smaller for a short specimen than for a large one.

Impact or static fracture surfaces were observed by SEM and TEM for the crack tip region. In the case of impact fracture, twin did not always appear and dislocation distribution was very complicated at the crack tip. And also, microscopic deformations of the specimen surface near the crack tip were measured by X-Ray micro beam diffraction method. In the case of impact fracture, micro lattice strain $\Delta d/d$ was large and it extended far from the crack tip.

Key Words : Impact Load, Steel, Crack Growth, Stress Waves, Twin, Electron Microscope Observation, X-Ray Diffraction Method, Low Temperature

1. Introduction

Recently, fracture mechanics has widely been used for studies of the crack growth behavior, but studies on crack growth due to an impact load have many theoretical and experimental difficulties⁽¹⁾ to be solved. However, the study on the crack growth behavior due to the impact load is necessary to ensure the safety design of a machine.

Hietherto, since the crack growth condition can be evaluated by dynamic stress intensity factor $K(t)$ and dynamic fracture toughness K_{Id} , various experimental methods to get K_{Id} have been proposed⁽²⁾. But specimen length and boundary condition affect impact fatigue life^{(3)~(5)}, and then it is also necessary to study such an effect on the crack growth even in the case of single impact. Since a stress wave generated by an impact load propagates in a specimen and the stress state in the finite specimen becomes very complicated one by the reflection and transmission at the boundaries of a specimen, it is very difficult to calculate $K(t)$ actually. This study is performed based on the stress wave form and also on the observation of microscopic aspects of the fracture surface near the crack tip.

The purpose of this study is to make clear the critical crack growth condition of a cracked steel specimen due to the impact load not only mechanically but also based on the microstructural aspect. It is supposed that impact fracture behavior different from static one is due to the interference effect of stress waves, and then the experimental results are discussed from a point of view of stress wave propagation.

Under given static tensile loading, an impact tension was imposed on a specimen at low temperature to avoid the generation of a plastic zone and a plastic wave.

In addition to this, after impact or static tension experiments, fracture surface near the crack tip was investigated by using an electron microscope and also microscopic deformations were measured by using X-Ray micro beam technique. Then, these results were compared with the static fracture and discussed.

2. Experimental Procedure

2.1 Material and specimens

The material used was a commercial carbon steel, SS41.

For impact tension experiment under a static tension loading, Double-edge-notched (DEN) specimens were prepared as shown in Fig. 1(a). Their lengths were set at 50, 100 and 150 mm to investigate the effect of the superposition of the stress wave and the specimens with different lengths were called S, M and L type specimens respectively as below.

Center-cracked-tension (CCT) specimens of which lengths were 50 mm were prepared for microscopic observation near the crack tip. For the sake of convenience to observe the micro structure, coarse grain size spec-

* Received 31st October, 1984.

** Professor, Faculty of Engineering, Tohoku University, Aramaki Aza Aoba, Sendai, 980 Japan.

*** Research Associate, Faculty of Engineering, Tohoku University.

**** Graduate Student, Tohoku University.

++ Faculty of Engineering, Tohoku University.

+ Lecturer, Department of Mechanical Engineering, Xian Jiatong University, Xian, Shaanxi, P. R. China.

imens were also prepared by heating at 1323 K for 30 hr. and subsequent cooling at the cooling rate of 5 K/h till 873 K for CCT specimens. After the heat treatment, the mean grain diameter of specimens was 0.17 μ m.

A Vibrophore type fatigue testing machine was used to introduce fatigue pre-cracks into both DEN and CCT specimens. For DEN specimen, fatigue load amplitude was 1.47 kN and total precrack length including notch depth was 5 mm. For CCT specimen, they were 1.6 kN and 6 mm, respectively. After precracking, they were annealed in vacuum at 923 K for 1 hr. Table 1 shows mechanical properties of this material.

2.2 Experimental apparatus

Figure 2 illustrates the experimental apparatus. Under a static tension 1.96 kN, a weight was dropped to apply an impact tension to the specimen.

2.3 Experimental methods

Three cases of experiments were carried out for different combination loadings. In each case, the specimen was cooled by soaking in liquid nitrogen to a brittle breakage.

2.3.1 Impact tension under static tension (effect of the drop weight size)

In impact fracture, characteristic fracture aspects due to the stress wave have been often observed⁽⁶⁾. So, in this study, the effects of rising rate of the stress wave form and its duration are discussed in detail. By using different sizes of drop weight, it is expected that these different characteristic parameters of impact loading form will be obtained⁽⁷⁾. Then three types of drop weights shown in Table 2 were used. The drop height to cause a fracture of the specimen was found out by increasing the height by 1 cm in every drop, and these preloads did not affect the fracture. This was confirmed by no change appearing in Vickers hardness near the crack tip after every impact. Specimens used in this experiment

Table 1. Mechanical properties

Yield Strength σ_{ys}	Tensile Strength σ_B	Elongation (G.L.=50mm) δ %	Reduction of Area ψ %
264 MPa	315 MPa	40.6	34.8

Fig. 1 Specimen geometry

were DEN type and their lengths were 100 mm.

2.3.2 Impact tension under static tension (effect of the specimen length)

As pointed out in impact fatigue⁽¹⁾⁽³⁾⁽⁵⁾, the rising rate, the maximum value and the duration of a stress wave form depend on the specimen length because of the superposition of stress waves even though the impact load is the same. Then, the effect of specimen length on the critical crack growth condition is studied, too.

A drop weight of 4 kg was used and the drop heights were set at 100 and 200 mm to get a constant impact load. Specimens used in this experiment were DEN type and their lengths were 50, 100 and 150 mm.

2.3.3 Tensile experiments under a constant impact load

To discuss the micromechanism of dynamic fracture, fracture surfaces near the crack tip were observed by using SEM and TEM, and microscopic deformation of the specimen surface near the crack tip was measured by X-Ray micro beam diffraction method.

In this case, the drop weight was 4 kg and the drop height was 250 mm. And CCT type specimens were used.

3. Experimental Results and Discussion

3.1 Effect of drop weight size on the fracture strength

Every stress wave form at the fracture was measured by using a strain gage pasted on the specimen surface near the crack tip 2.5 mm apart from the side edge. Figure 3 shows a typical example of this stress wave

Table 2. Dimensions of drop weights

Type	4L	2.5S	2.5L
Mass (kg)	4	2.5	2.5
Length (mm)	200	121	200
Outside diameter (mm)	70	70	60
Inside diameter (mm)	40	40	40

Fig. 2 Experimental apparatus

form. This form can be expressed simply as shown in Fig. 4 and two parameters, the stress rising rate $\dot{\sigma}_d$ and $F = \sigma_d \tau / 2$, are defined to discuss experimental results. Where τ is the time taken to cause a fracture. In Fig. 5, as a whole, σ_d tends to decrease with an increase of σ_s . In $\sigma_s < 60$ MPa, σ_d is independent of σ_s and nearly constant. In $\sigma_s > 60$ MPa, σ_s and σ_d are linearly related and this implies the equivalence between them, where σ_d is an impact stress at the fracture point of the simplified wave form and σ_s is a nominal static tensile stress.

In Fig. 6, σ_s is equal to zero, σ_f has the smallest value and it corresponds to the most dangerous case, where σ_f is a sum of σ_d and σ_s . In the case of $\sigma_s < 60$ MPa, σ_f is nearly constant, that is, this figure also suggests equality between σ_s and σ_d . On the other hand, Figs. 5 and 6 show the drop weight size dependence. From these results, it will be seen that σ_f cannot explain the impact fracture strength.

Now, it is desirable to find out a proper parameter which can give a unified explanation for the experimental results. In Fig. 7, though experimental values are scattered, the following equation can express the relation between $\dot{\sigma}_d = \sigma_d / \tau$ and σ_s , where $\dot{\sigma}_d$ and τ are stress rising rate and rise time as in Fig. 4.

$$\dot{\sigma}_d = A - B\sigma_s \quad (1)$$

where A and B are experimental constants. In this figure, the linear relation depends

on the drop weight size and it alone cannot explain the experimental results. Then, in the next, the relation between F and σ_s is shown in Fig. 8, where F is a product of σ_d and τ as in Fig. 4 and it means energy dissipated during the fracture. Although little scattering can be seen in this figure, F is almost independent of σ_s and is nearly constant in every drop weight, and then this relation can be expressed as

$$F = \sigma_d \tau / 2 \quad (2)$$

Substituting Eq. (2) into Eq. (1), we obtain

$$\sigma_d^2 = A' - B'\sigma_s \quad (3)$$

where A' and B' are constants. This expression is very similar to the tendency shown in Fig. 5.

By the way, σ_d is the stress at the moment of fracture on the stress wave form and it seems to be related not to the start of the crack growth but to the fracture of specimen. In order to know the crack growth point more accurately, dynamic stress condition should be measured before the final fracture.

3.2 Effect of specimen length on the critical crack growth condition

At first, the effect of the specimen length on the critical crack growth condition is studied. An electric circuit was used to detect the crack growth point as shown in Fig. 9. Conductive silver composition was painted after the insulation with

Fig. 3 Typical example of stress wave form

Fig. 4 Parameters of simplified wave form

Fig. 5 Relation between σ_s and σ_d

Fig. 6 Relation between σ_s and σ_f

Fig. 7 Relation between σ_s and $\dot{\sigma}_d$

a shielding painting at the crack tip. Then it was connected to the wave memory and a strain gage in series. When a growing crack cuts this painted circuit, it is recorded on the stress wave form. A typical example is shown in Fig. 10. It is characterized by defining three parameters as shown in the same figure. Where suffix "c" means the stress when the electric circuit is cut. In this experiment, a strain gage was pasted on the central line of the specimen 15 mm apart from notches, and so the stress wave form was obtained. In Fig. 11, impact stress σ_{cd} is independent of static stress σ_{cs} and nearly constant for $\sigma_{cs} < 50$ MPa. In $\sigma_{cs} > 50$ MPa, σ_{cd} decreases linearly with an increase of σ_{cs} and the equivalence can be seen between them as mentioned in the explanation of Fig. 5. That is, the result of Fig. 11 is in agreement with that of Fig. 5 qualitatively. But they cannot be compared with each other directly because the drop height is not the same. In addition to this, an experimental curve of L type specimen is different from that of M type specimen for the same drop height, that is, effect of specimen length is seen. The difference between these two experimental curves becomes smaller with an increase of σ_{cs} . Thus, the fracture strength due to a single impact load is also influenced by the specimen length in the direction of the stress wave propagation as in the case of impact fatigue.

Fig. 8 Relation between σ_s and F

Fig. 10 Typical example of stress wave form and its parameters

In Fig. 11, the experimental result of S type specimen seems to be inappropriate to discuss the mechanical condition for the crack growth together with other M and L type specimens since the dynamic stress state becomes so complicated in the case of steel specimen that an accurate stress evaluation is difficult.

In Fig. 12, σ_{cf} takes the smallest value and then it is the most dangerous when σ_{cs} is zero, where σ_{cf} is a sum of σ_{cd} and σ_{cs} and it means an effective stress for the crack growth. With an increase of σ_{cs} , σ_{cf} tends to be saturated and this suggests the equivalence between σ_{cs} and σ_{cd} . And their relations depend on specimen length. Since mechanical properties of this material, for example, yield strength, do not change very much in the range of impact speeds of present experiments, the results shown in Figs. 11 and 12 are understood by considering the mechanical size effect on the impact load⁽¹⁾.

In order to confirm this point, the relations between σ_{cs} and $\dot{\sigma}_{cd} = \sigma_{cd}/\tau_c$ for L and M type specimens except for S type are compared in Fig. 13. In this figure, $\dot{\sigma}_{cd}$ of M type specimen is steeper than that of L type specimen. This is a natural result, because many reflected waves are superposed in M type specimen than in the case of L type specimen. In Fig. 11, at $\sigma_{cs} = 0$, a longer specimen needs longer time till the

Fig. 9 Electric circuit for detecting crack growth

Fig. 11 Relation between σ_{cs} and σ_{cd}

stress reaches a proper fracture strength of the material. However, a higher stress at a crack tip releases it at every wave superposition and then stress is gradually averaged over the width of specimen. Thus, even if a stress reaches the critical value which is material's proper strength at the crack tip, the stress of a longer specimen is higher than that of a shorter one at the measuring point due to the distributed stress averaged over the specimen width. Therefore, in the present study, the stress in an L type specimen at the crack growth turned out higher than that in an M type specimen. It is very difficult to evaluate the effects of wave reflection and diffraction at the crack tip, but dynamic stress analysis of a finite body should be performed in future.

In the next, fracture behavior of crack-grown specimen is discussed based on the stresses at the start of crack growth. In this way, the relation between σ_{cs} and $F_c = \sigma_{cd} \tau_c / 2$ is shown in Fig. 14, where F_c means energy dissipated before a crack starts to grow. Of course, this F_c is different from F described in previous section. The relation shown in Fig. 14 can be expressed as follows.

$$k F_c + \sigma_{cs} = 120 \quad (4)$$

where k is a constant which depends on the specimen length and on the drop height. By using this relation (4), F_c can be estimated

Fig. 12 Relation between σ_{cs} and σ_{cf}

Fig. 13 Relation between σ_{cs} and $\dot{\sigma}_{cd}$

for any h and L . However, further experiments will be needed using a lot of specimens to confirm this relation (4). And also some studies will be necessary for the scattering of impact fracture strength. Nevertheless, F_c is a more suitable parameter than F to explain the results of the present study.

3.3 Observation of fracture surface near the crack tip

In addition to the above discussions concerned with the mechanical properties, structural aspect should be also considered. For the observation of the fracture surface near the crack tip, CCT specimens were used and fracture surfaces caused by impact load and static one were compared with each other.

Figure 15 shows a typical example of fractographs of a coarse grained specimen observed by SEM. Although some twins can be seen in both static and impact fracture surfaces, they were more in the former than in the latter for which twins are observed in crystal grains little apart from the crack tip. From this result, it is considered that twin does not always act as a trigger of the crack growth when an impact load is imposed. Twin observed on the surface coincides with that on the fracture surface. In the impact fracture, most of structural patterns were not straight slip lines but river patterns on the fracture surface. Unless twin is the trigger of the crack growth in the impact fracture, it is likely that slip lines play an important role in the growth of a crack. In order to investigate this, slip lines and distribution of dislocations near the crack tip were observed by TEM. For these observations, fine grained specimens were used, and replicas and thin films were taken from the portion of the crack tip as observation samples after the fracture.

Figure 16 shows specimen surface aspects by replica. Slip lines are distributed in parallel over a wide area in the static fracture. On the other hand, there are fine irregular portions in which parallel short slip lines are distributed in the impact fracture and the gap between slip lines is wider than that in the static one. These differences in the distribution of slip lines can be related to the distribution of dislocations as shown in Fig. 17. Dislocations are distributed in parallel and

Fig. 14 Relation between σ_{cs} and F_c

uniformly in the static fracture, but they show cell structures in the impact fracture. This is not always in agreement with previous study⁽⁸⁾ because these dislocations were observed near the crack tip and thus they could be affected by complicated dynamic stress state due to the stress concentration of the crack.

In the next, to discuss the microscopic deformation at the crack tip quantitatively, micro lattice strain $\Delta d/d$ and total misorientation β of the specimen surface δ mm apart from the fracture surface were measured by X-Ray micro beam diffraction method as shown in Figs. 18 and 19. $\Delta d/d$ itself is larger and microscopic deformations extend far from the fracture surface in the impact fracture. This suggests that dislocation sources can act far from the crack tip in the impact fracture.

4. Conclusions

The results are summarized as follows.

Under a static tensile loading, an impact tension was imposed on a specimen at 77 K.

- (1) Impact stress σ_d was independent of static stress σ_s and nearly constant in the lower range of σ_s .
- (2) The relations between σ_s and σ_f , σ_s and σ_d , σ_s and F were obtained. But drop weight size affected these relations.

The effect of specimen length on the critical condition of crack growth was discussed using characteristic parameters which expressed the stress wave form.

- (3) Impact stress σ_{cd} at the crack growth was independent of applied static stress σ_{cs} and was nearly constant in the lower range

of σ_{cs} . In the same range of σ_{cs} , specimen length affected σ_{cd} and it was smaller for shorter length specimen. But in the higher range of σ_{cs} , σ_{cd} did not depend on specimen length and decreased with an increase of σ_{cs} .

Impact or static fracture surfaces were observed by SEM and TEM for the crack tip region.

- (4) Twin did not always appear at the crack tip in the impact fracture. The specimen was more irregular for impact fracture than

Fig. 17 Distribution of dislocations near the crack tip

Fig. 15 Twins of the fracture surface

Fig. 16 Specimen surface aspects near the crack tip

Fig. 18 Distribution of micro lattice strains

Fig. 19 Distribution of total misorientations

for static fracture. On the irregular surface, slip lines were very short in the case of impact fracture.

(5) Dislocations were distributed in parallel and uniformly in the static fracture. But in the impact fracture, they were complicated and showed cell structures.

Microscopic deformation near the crack tip was measured by X-Ray micro beam diffraction method.

(6) Micro lattice strain $\Delta d/d$ was larger and extended far from the fracture surface in the impact fracture.

Acknowledgment

This study was supported by Scientific Research Fund from the Japanese Ministry of Education.

The authors are grateful to H. KATSUTA and K. TOMOBE who assisted them in these experiments as a part of their graduation theses.

References

- (1) Maekawa, I., J. JSME (in Japanese), Vol. 84, No. 750 (1981-5), p. 448.
- (2) Kunio, T. et al., Experimental Methods of Fracture Mechanics (in Japanese), (1984), p. 107, Asakura Shoten.
- (3) Maekawa, I. et al., Proc. ICF. Int. Symp. Frac. Mech., Beijing (1983), p. 757.
- (4) Maekawa, I. and Hita, J., J. SMS (in Japanese), Vol. 29, No. 320 (1980-5), p. 486.
- (5) Maekawa, I. et al., Proc. 25th Japan Cong. Mater. Res., (1982), p. 124.
- (6) Jhonson, W., Impact Strength of Materials (1972), Edward Arnold.
- (7) JSME, Rep. RC-SC8 (in Japanese), (1967) p. 36.
- (8) Leslie, W. C. et al., J. Iron Steel Inst., No. 200 (1962), p. 622.