Research paper

Microfractography of fracture surface of a carbon steel tube caused by contact detonation

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Abstract

In the case of closer detonation of high explosives to a structure such as attack of terrorism, the target is exposed to the extremely high pressure and temperature ina very short time. It is important to focus on the damage quantity of the structure under such environment, and its fracture mechanism. The small-scale explosion experiments are carried out. The high explosive Composition C-4 is exploded at the axial center of the outer surface of a carbon steel tube, STPG370. The weight of explosive and the standoff are parameter values. This paper presents the relationship between the standoff and the damage quantity of the tube, and the results of microfractography of the fracture plane using the scanning electron microscope (SEM) to clarify the fracture mechanism of the material.

Keywords : Microfractography, Carbon steel tube, Detonation, Fracture, C-4

1. Introduction

The mechanism of plastic deformation and fracture phenomenon by detonation are one of the important concerns in damage kinetics. Especially, in the case of closer detonation of high explosives to a structure, it is under the environment of extremely high pressure larger than a gigapascal pressure and high temperature at a few thousand degrees ina very short time. The material is deformed plastically or fractured at very high strain rate caused by that environment. Some experimental researches on the behavior of concrete plate which is the brittle material have been carried out under such condition[1)-3)]. In the three-dimensional structure, some experimental studies using metal tubes have been performed[4)5)]. In these studies, the detonation occurred inside the tube. Little is known about the microscopic fracture mechanism in these studies.

Recently, the threat of terrorism has been growing in the world. The most typical measure in terrorism is an attack by explosives. Then, a structure may be shocked from the exterior. Therefore, it is also important to focus on the damage of the material caused by the detonation which occurred outside of structure. In this study, the small-scale explosion experiments in which the detonation occurred outside of structures were carried out. The carbon steel tubes were adopted in the experiments. The carbon steel is ductile at normal temperature. In this paper, the damage quantity of the material caused by detonation and the fracture mechanism based on microfractography of fracture plane are discussed.

2. Experiments

2.1 Experimental methods

In this study, carbon steel tube, STPG 370 (JIS G 3454) was used as the target for explosion experiments. The dimensions of the tube are 300 mm in length, 165 mm in outer diameter and 5.5 mm in thickness. As explosive material, Composition C-4 whose density is 1.4 g cm^{-3} was adopted. It is extremely stable and complete explosion takes place even if it is small amount, and can be molded into any desired shape. Therefore, Composition C-4 is more adapted for this kind of small-scale experiment than TNT[6)]. A No. 6 electric detonator was used as primary explosive, and the tip of that was installed at the center of cube-shaped Composition C-4 wrapped with plastic sheet.

Figure 1 shows an experimental system. The tube was placed horizontally by the chain which passes through the tube. To simulate the situation of the floating tube in the air, the tube was not fixed to the trestle. The chain was only hung with the tube and can be moved freely. All ex-

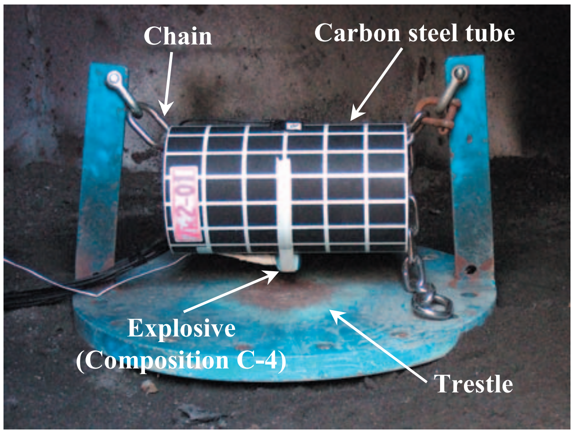


Fig. 1 The example of experimental system.

Table 1 Experimental conditions.

Case No.	Explosive weight, W [g]	Standoff, R [mm]	Scaled distance, λ [m kg$^{-1/3}$]
1	25	0	0
2	100	0	0
3	100	25	0.054
4	100	50	0.108
5	100	75	0.162

periments were carried out with an explosion chamber of 2 m in height and 2 m in width. The chain also plays a role to prevent that the tube clashes to the inner concrete wall of explosion chamber. The installation location of explosive was the center of axial direction at outer surface of the tube which did not overlap with the welding seam. The structure material of the trestle is a carbon steel, SS400.

2.2 Experimental conditions

The weight of explosive W, and the standoff R which is the distance between the lowest part of outer surface of the tube and the upper surface of the explosive are the parameters. Table 1 shows experimental conditions in this study. The weight of explosive was 25 g or 100 g. The experiments of the standoff which was not equal to zero were carried out only in the explosive of 100 g in weight. The range of the scaled distance, λ is from 0 to 0.162 m kg$^{-1/3}$.

The distance of standoff was set by a paper spacer so as to avoid the disturbance on the effect of detonation. Regardless of experimental conditions, the distance between the plane of the trestle and the lower surface of the explosive was kept constant with 30 mm. All the tubes used in the experiments were the products of the same lot.

3. Results of experiments

3.1 Effect of the scaled distance

The experimental results organized to measure the plastic deformation and fracture of the tube, are shown in Table 2. The through−hole caused by the fracture of the tube was generated only in the cases of contact detonation in which standoff was equal to zero. When the weight of explosive was 25 g in the case No. 1, a circular through−

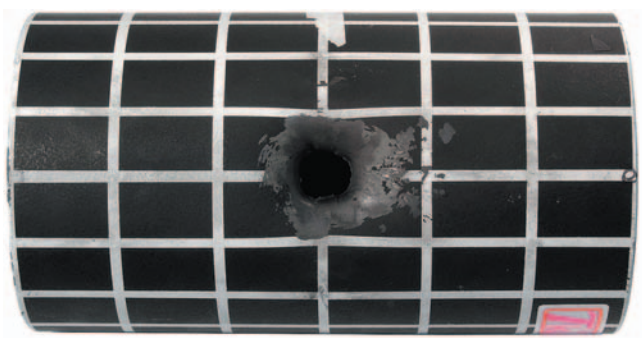
Table 2 Experimental results.

Case No.	Averaged diameter of through−hole [mm]	Depth of dent [mm]	Diameter of dent a : major axis b : minor axis [mm]
1	23	—	—
2	100	—	—
3	—	75	a : 230 b : 160
4	—	50	a : 190 b : 150
5	—	35	a : 160 b : 100

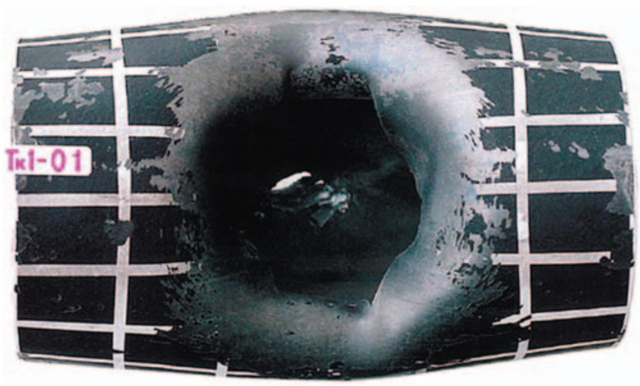
hole of 23 mm in diameter with dent was generated in the center of explosion. However, the damage was only limited around that location. The cross section of the tube maintained circular form.

Meanwhile, in the case No. 2 with the explosive of 100 g in weight, the tube was wholly plastically−deformed and the large through−hole was generated. The through−hole turned up toward the inside of the tube in four directions due to progress of the cracks generated on the tube. The averaged diameter of the through−hole in this case is about 100 mm. Moreover, the fracture which is about 30 mm of axial crack was generated at the symmetrical location of the center of explosion on the tube (See Fig. 2).

In the cases not of contact detonation, the tubes deformed plastically without fracturing (See Fig. 3). It is found that even a narrow standoff is effective to prevent

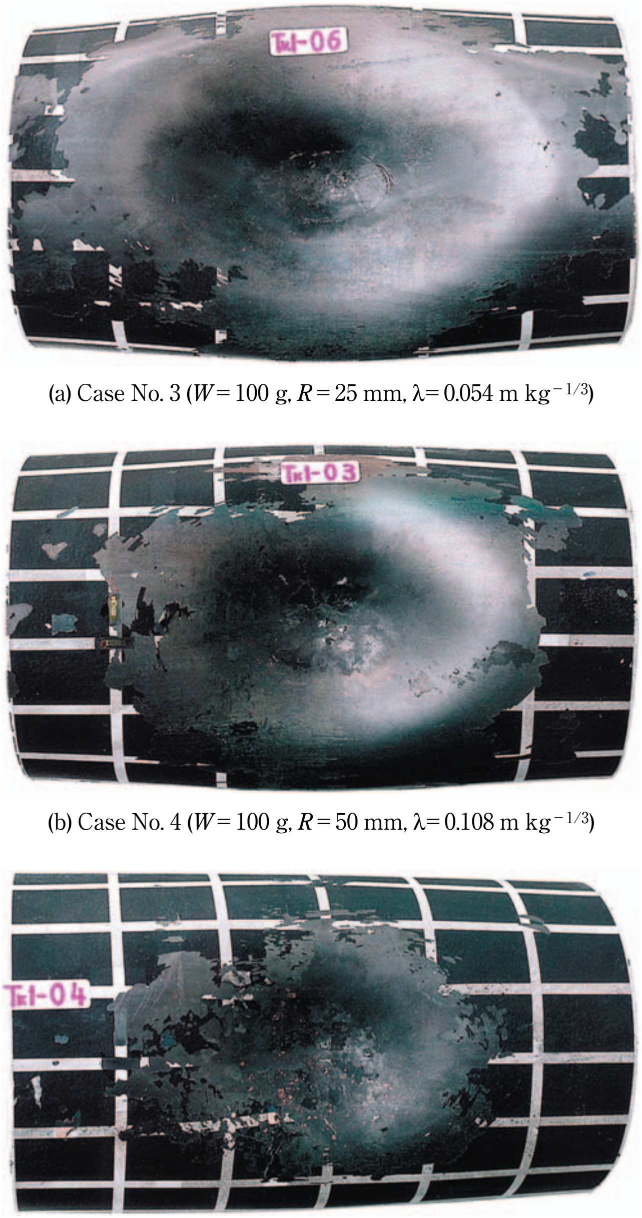


(a) Case No. 1 (W = 25 g, R = 0, λ = 0)



(b) Case No. 2 (W = 100 g, R = 0, λ = 0)

Fig. 2 The view of the tube from the side of hypocenter after the experiment.



(a) Case No. 3 ($W = 100$ g, $R = 25$ mm, $\lambda = 0.054$ m kg$^{-1/3}$)

(b) Case No. 4 ($W = 100$ g, $R = 50$ mm, $\lambda = 0.108$ m kg$^{-1/3}$)

(c) Case No. 5 ($W = 100$ g, $R = 75$ mm, $\lambda = 0.162$ m kg$^{-1/3}$)

Fig. 3 The view of the tube from the side of hypocenter after the experiment.

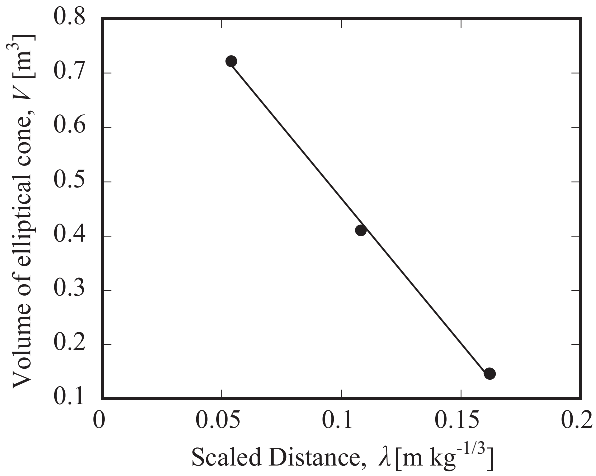


Fig. 4 The relationship between the scaled distance and the volume of elliptical cone.

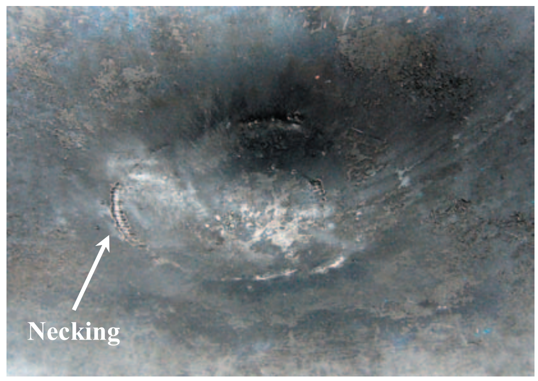


Fig. 5 The necking at the dent part in the case No. 5 (the scaled distance is 0.054 m kg$^{-1/3}$).

the fracture of the structure. The axially long elliptical dent was generated on the center of explosion. Assuming that the shape of dent is elliptical cone, then the volume of the elliptical cone V is calculated by the following equation[7].

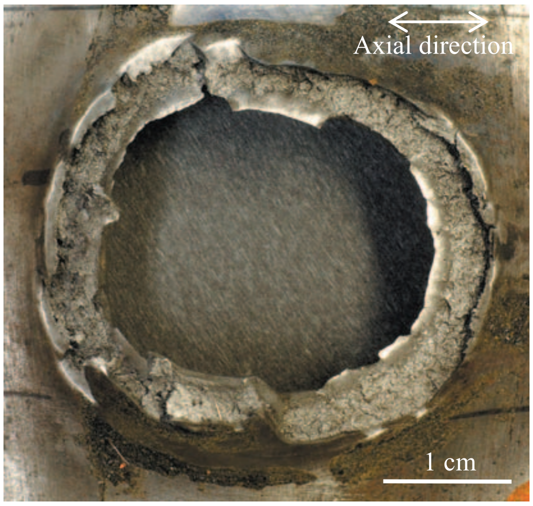
$$V = \frac{\pi}{12} abD \tag{1}$$

Where a is the major axis, b is the minor axis and D is the depth of the dent. The relationship between the scaled distance and the volume of elliptical cone is shown in Fig. 4. The volume of elliptical cone decreases inversely with the standoff. Figure 5 shows the dent part of the tube in the case No. 3, where the standoff is 25 mm (the scaled distance is 0.054 m kg$^{-1/3}$). At the dent part, the necking which causes local elongation was observed. It was generated on the circumference of ellipse which has about 6 cm in major axis and 3 cm in minor axis. From this result, it might be inferred that the material reaches fracture toughness when the standoff is shorter than 25 mm because of increase of impact pressure as well as reduction of elongation caused by the increase of strain rate[8].

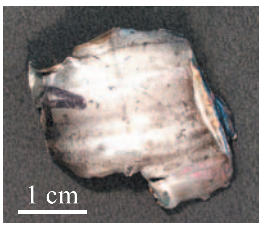
3.2 Fractography of the fracture planes

In the experiments, it was found that only the conditions of contact detonation resulted in fracture of the tubes. In order to ascertain the fracture mechanism, the fractography was carried out in the case No. 1 with the explosive of 25 g in weight. Figure 6 shows the fracture region observed from the inside of the tube, and the fragment which was separated from the tube. In this figure, the positional relationship of the fracture region of the tube and the fragment conform each other. It is found that the through-hole is nearly circular form. Macroscopic features of the fracture plane of the tube and the fragment are clearly different between the middle part and the edge part of the fracture plane. The middle part of the fracture plane is the glittery granular fracture. On the other hand, the edge part of the fracture plane is gray smooth surface. The feature in the middle part occupies large part of the fracture plane. On the fracture plane, the clear feature of a source of fracture such as radial marks generated in Charpy test is not observed.

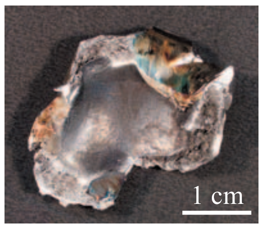
In this paper, the microfractographic features in the five regions specified in the Fig. 7 are shown below. Region1A and Region1B are the edge part of the fracture plane of



(a) Fracture region of the tube (Inside of the tube)



(b) Fragment (Inside of the tube)



(c) Fragment (Onside of the tube)

Fig. 6 The fracture region of the tube and the fragment.

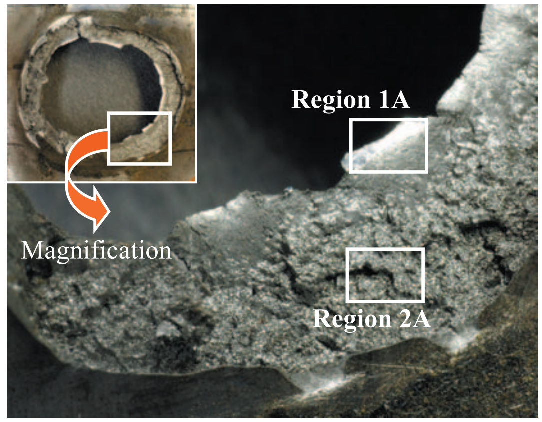
the tube and the fragment, respectively. Region 2A and Region 2B are the middle part of the fracture plane of the tube and the fragment. The relationship between Region 1 A and Region 1B is mutual corresponding fracture regions between the tube and the fragment as well as the relationship between Region 2A and Region 2B. As shown in Fig. 6, a part of material which was not fractured in the shape of a circle remained in the tube. Region 3 is the edge in the forefront of this part.

The low vacuum scanning electron microscope, LV−SEM (JSM−5600LV made by JEOL) was used for microfractography. The fracture region of the tube was extracted from the tube as the specimen for microfractography. Before microfractography, ultrasonic cleaning in acetone was practiced for the fracture plane of the tube and the fragment.

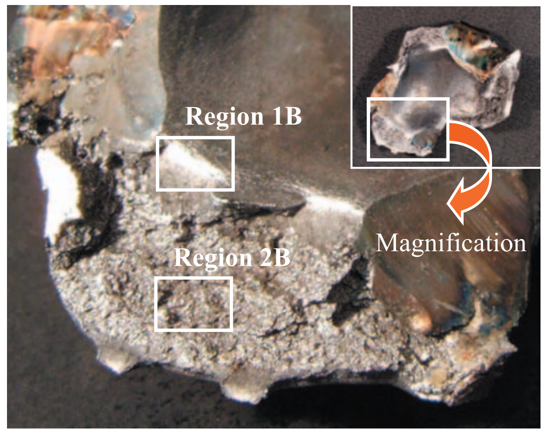
The typical microfractographic features in Region 1A and Region 1B are shown in Fig. 8. The image of Region 1 B is the mirror image for easy understandable comparison with Region 1A. In these regions, elongated dimples are observed in the both fracture planes. The directions of the dimples in each fracture plane are opposite mutually. This clearly shows that the failure in these regions is ductile fracture caused by not tear stress but shear stress.

Figure 9 shows the typical microfractographic features in Region 2A and Region 2B. In these regions, the mixed mechanism of the fracture which is the cleavage planes and river patterns with dimples are observed. This feature shows the quasi−cleavage fracture plane. Therefore, the failure in these regions is brittle fracture.

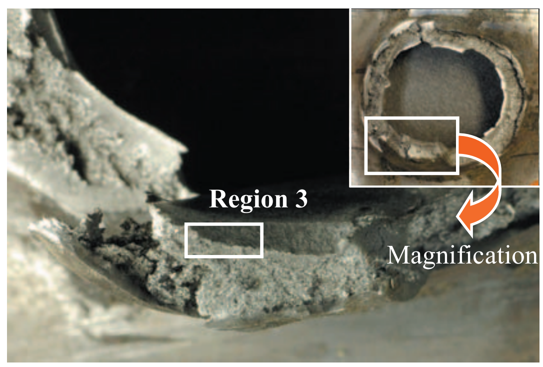
In other regions of the middle part and the edge part of



(a) Observation regions of the fracture plane on the tube



(b) Observation regions of the fracture plane on the fragment

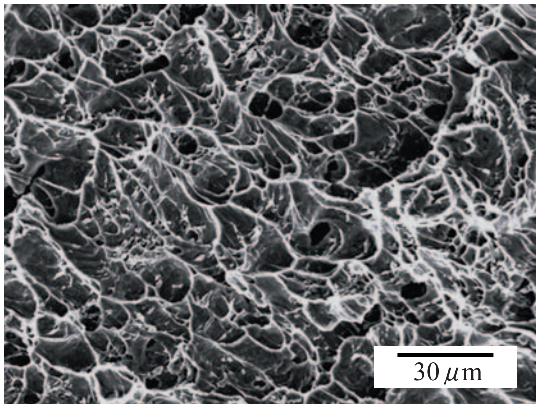


(c) Observation region of the fracture plane on the tube

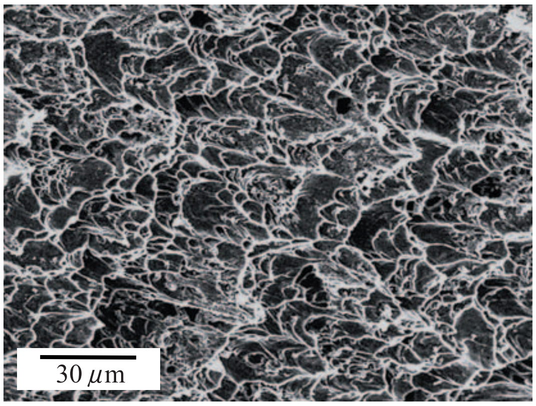
Fig. 7 The observation regions of the fracture plane.

the fracture plane, the same features were observed. Although detonation gas has high temperature at a few thousand degrees, the feature of creep fracture is not observed on this fracture plane.

The results of macrofractography and microfractography show that the fracture is caused by the following process. Firstly, the dent as plastic deformation was formed by uniform elongation caused by detonation pressure when the detonation occurred. Secondly, the ductile fracture caused by the slip which was shown as the elongated dimples occurred on outer surface of the dent when the stress exceeded ultimate strength of the material. Finally, the stress reached actual breaking stress immediately after the ductile fracture. Then the brittle fracture occurred on the circumference of circle simultaneously.

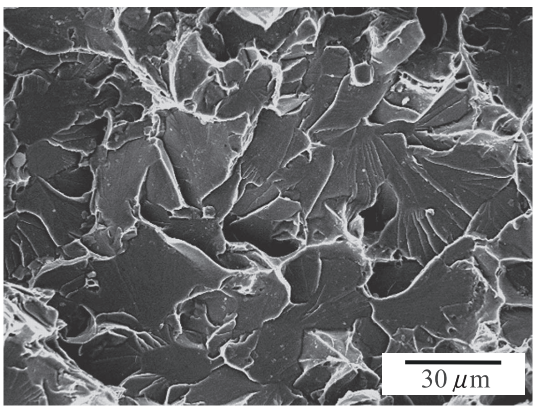


(a) The typical feature of Region 1A

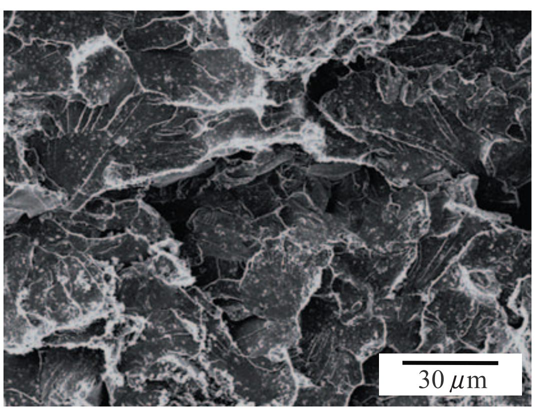


(b) The typical feature of Region 1B

Fig. 8 Microfractography in Region 1A and Region 1B.



(a) The typical feature of Region 2A



(b) The typical feature of Region 2B

Fig. 9 Microfractography in Region 2A and Region 2B.

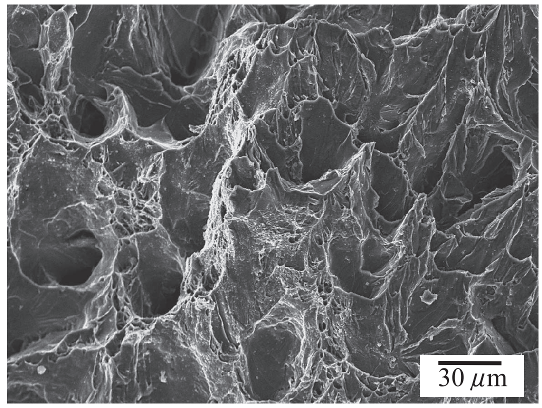


Fig.10 Microfractography in Region 3.

In Region 3, the equiaxed dimples which are generated by the tensile stress are observed (See Fig. 10). It indicates that the fragment was separated from this location of the tube finally by the tensile stress in the same direction as detonation pressure.

4. Conclusions

In this study, the small-scaleexplosion experiments were carried out. In the contact detonation, the through-hole was generated when the weight of explosive was not only 100 g, but also 25 g. On the other hand, when the standoff was 25 mm (the scaled distance was 0.054 m $kg^{-1/3}$), the through-hole was not generated even in the case of 100 g explosive weight. It shows that even a narrow standoff is effective to prevent the fracture of the structure.

Macro- and microfractography of the fracture plane in the contact detonation by 25 g explosive weight was carried out. From the analysis of this observation, it is found that the circular through-hole is generated in a very short time under almost brittle fracture, after the dent is formed by uniform elongation.

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接触爆発に起因する炭素鋼管破断面の微視的破面観察

澤田健一

テロ攻撃等において，構造物の極近傍域で高性能爆薬などによる爆轟が生じた場合，その対象物は，瞬間的に極めて高圧・高温の環境に曝される。セキュリティ向上のためには，このような環境下における，構造物の被害量及びその破損メカニズムを明らかにすることが重要となる。本研究では，爆破対象として炭素鋼管（STPG370）を用いた小規模な爆破実験を行った。爆薬には高性能爆薬C－４を使用し，鋼管外表面中央部を爆発中心とした。実験は，爆薬量とスタンドオフをパラメータとして実施した。本論文では，スタンドオフと被害量の関係の評価，及び破損メカニズムを明らかにするために走査型電子顕微鏡による鋼管破断面の微視的破面観察を行った。

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