Research paper

Examination of the break-up model for explosion break-up analysis
(The explosion break-up experiment which used the aluminum cylinder for the target)

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Abstract

It may be explosion break-up and the accident has actually occurred, such as explosion breakup of a plant, a satellite, a rocket, and the machines which became high temperature and high pressure more. That accidental explosion break-up generally causes catastrophic hazard to the surroundings. Therefore, it is important to understand the mechanism that explosion breakup. In this study, a high explosive pentaerithritoltetranitrate (PETN) etc. is exploded using central axis explosion technology, and the high speed deformation and fracture behavior in an explosion break-up experiment are measured. And we are making examination and modification of Grady's model which are a kind of break-up model using the experiment result.

This presentation is scheduled for report the explosion break-up experiment which used the aluminum cylinder for the target. The observed behavior is reproduced by the numerical simulation using Autodyn 2D, and a Grady's model is considered for fragmentation.

Keywords: Cylinder expansion, Explosive loading, Shock wave, A5052

1. Introduction

The knowledge of high speed deformation and fracture is necessary for fracture control and safety evaluation of high energy industries and syntheses of materials very much. Explosive loading devices had been developed as simple experimental methods to supply impulsive loads for the study of dynamic responses or processes. Hiroe *et al.* [1), 2)] had proposed planar and cylindrically imploding wave generators, where a tabular plate and a cylindrical hollow of PETN (pentaerithritoltetranitrate) are initiated by the simultaneous explosion of parallel copper wire rows or etched copper bride wires placed over the entire outer surfaces using an impulsive discharge current from a capacitor bank. In a cylindrically diverging wave generator of Hiroe, *et al* [3)]., PETN column was initiated by the explosion of a bundle of copper wires at the central axis. These one dimensional wave generators seem to be applied rather simply to give basic shock loadings for plates, cylinders and rods of materials. The cylindrically expanding detonation had been applied to investigate dynamic responses of metallic cylinders at high strain-rates. In other studies, Forrestal *et al.* [4)] also achieved uniform expansion of cylinders explosively at the strain rate order of 10^3 s^{-1}. Grady[5)] proposed a fragmentation model for exploding explosive-filled steel cylinders, detonated at one end. In this paper, deformation and fragmentation for explosively exploding various Al cylinders are studied experimentally and numerically based on uniform expansion comparing with axially phased expansion.

Recently the authors had researched on high speed deformation and fracture of carbon steel and SUS304 using planar and cylindrically imploding wave generators. In this paper we made the experiment on high speed deformation and fracture of A5052 as a target using the wire explosion techniques and discussed these results.

2. Experiments

2.1 Experiment system

In this experiment uniform expansion of cylindrical material in axial direction was important. A high pressure load

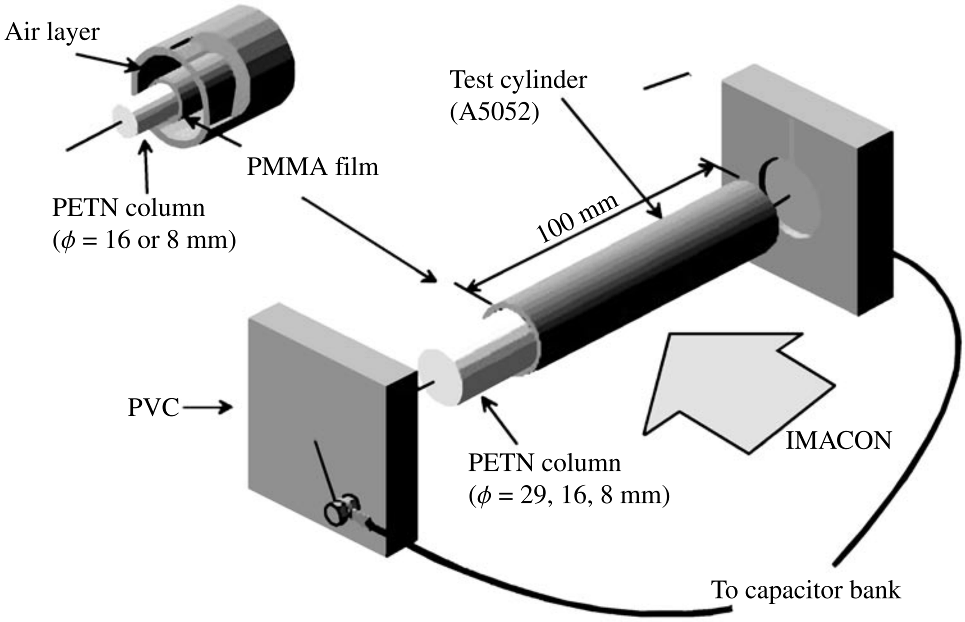
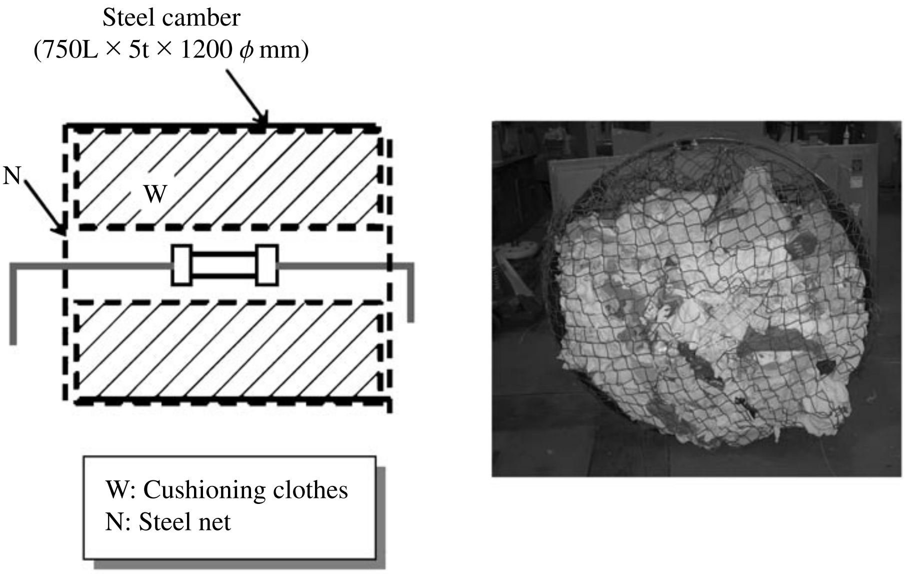


Fig. 1 Schematics of explosion test cylinder.

was imposed on the cylindrical material by the explosion which broke out at the centeral axis of the test cylinder. In this study, we made the experiment of explosion using the wire explosion techniques with PETN. Experiments are performed utilizing the explosion test facilities at the Shock Wave and Condensed Matter Research Center, Kumamoto University.

Figure 1 shows the present test rig. A5052 cylinder was used as the test cylinder (o.d 35 mm, thickness 3 mm, length 100 mm). This test system was consisted of a large volumetric condenser and the test metallic cylinder. At the center of the test cylinder, a bundle of three copper wires (ϕ =0.175 mm) was set and PETN was packed in the cylinder at charged density 0.90-0.95 g / cc. As a detonator, firstly a large amount current from the condenser of 40 kV, 12.5 μmF streamed into the copper lines and the copper lines exploded and vaporized instantaneously. Secondly, explosive PETN was exploded by a shock wave which was generated by the suddenly increase of pressure with the vaporization and the shock wave transformed into cylindrical expanding detonation wave over time. The detonation wave reached the wall of test metallic cylinder, and the cylinder was expanded and broken uniformly in radial direction. We called this technique as the wire explosion technique. The diameter of PETN column was 29 mm, 16 mm, 8 mm and explosive PETN was packed in the cylinder made of PMMA (polymethyl methacrylate) film which was 50 μs thickness and had lower shock impedance.



(a) Image (b) Photograph

Fig. 2 Schematic of test chamber for recovering fragments of explosion metal cylinder.

(a) PETN column of ϕ29 (b) PETN column of ϕ16 (c) PETN column of ϕ8

Fig. 3 A photograph of recovery fragments of A5052 cylinder.

2.2 Recovery of fractured cylinder

After explosion and breaking, fragments were collected and condition of fragment was researched. In the case of breaking of metallic materials under high speed distortion conditions, a number of fragments with large energy spread. But, the collection of fragment without change after explosion as much as possible is necessary in order to research and estimate the data of stress response of materials. In our laboratory the recovery system of fractured cylinder was developed as seen in Fig. 2. This recovery system consisted of steel thin cylinder and cotton wastes were packed at the inner of the steel cylinder. Test cylinder was set at the center of the steel cylinder. The present recovery system has the high collection rate, since most fragments of the cylinder were stopped inside of the steel cylinder by cotton wastes.

Figure 3 shows fragments collected by the present recovery system. From this photography it is found that the size of fragments became smaller and the number of one increased when the diameter of PETN column became larger. These data on fragment state is available for the prediction of an explosive accident and the estimation of an explosive yield. Further the data were useful for the calculation of breakup energy.

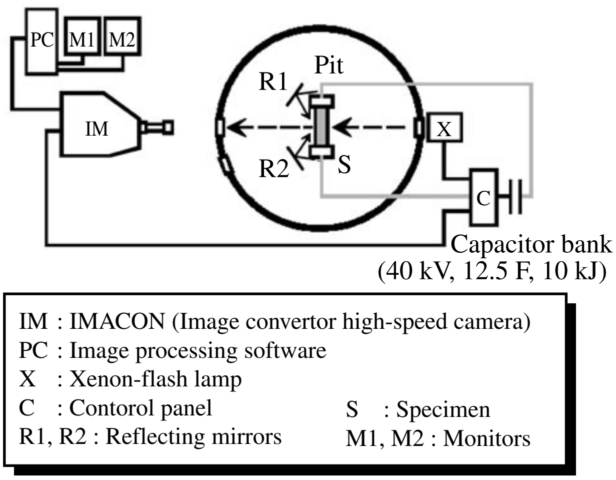


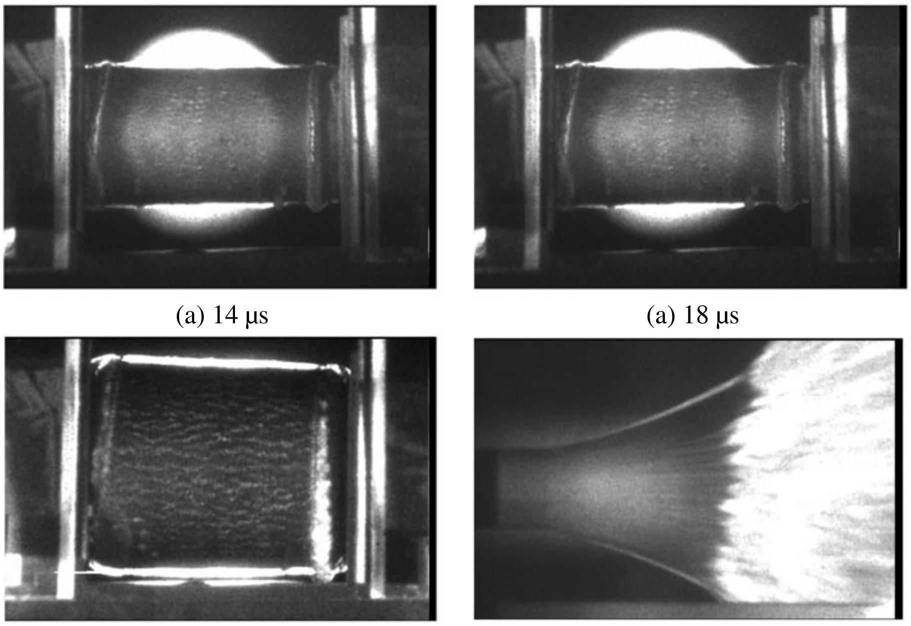
Fig. 4 Schematics of photography test by IMACON.

2.3 Observation of expansion and deformation behavior

Image Converter High-Speed Camera (abbrev. IMACON) was used to observe the behavior of expansion and the surface of test cylinder. Figure 4 shows the observation system. The light sorce for the visualization of outline of the test cylinder was Xenon-flash lamp. And a flash caused by copper wire explosion was used as the light sorce in order to observe the surface of the test cylinder. The flash was reflected by a mirror and lighted on the target.

Figure 5 shows the observation result at PETN ϕ =29 mm. These photographs were taken under good conditions and captured the processes of breaking of the target. Furthermore annularly-shaped pattern could be seen on the surface of the test cylinder. This pattern was shown in the case of the deformation at a high strain rate. It was found that many cracks appeared on the surface of the cylinder and the cylinder was broken.

Figure 6 shows the result of history of expansion of the test cylinder obtained from the photographs of streak in Fig. 5(d). If the volume of the test cylinder was same before and after breaking, the size of collected fragments was measured, and the diameter of the cylinder could be estimated. From these measurement results and result of history of expansion in Fig. 6, we can determine breakup time, expansion velocity and strain rate. These results are shown in Table 1. Since the diameter of the test cylinder at the time of destruction was different for every diameter of PETN column, we found that the breaking factor didn't depend on only the diameter of the cylinder.



(a) 14 µs (a) 18 µs

(a) 22 µs (a) Streak

Fig. 5 Framing record of explosion A5052 cylinder for IMACON. (ϕ_{out} =35 mm, t =3 mm, PETN ϕ =29 mm)

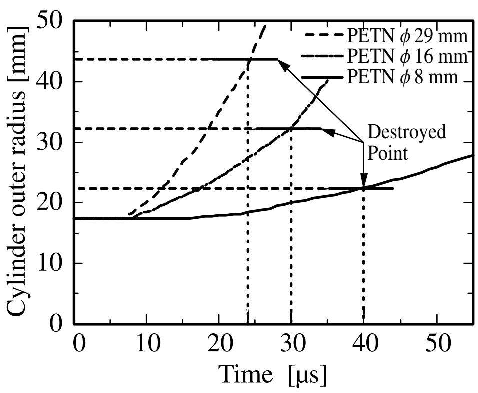
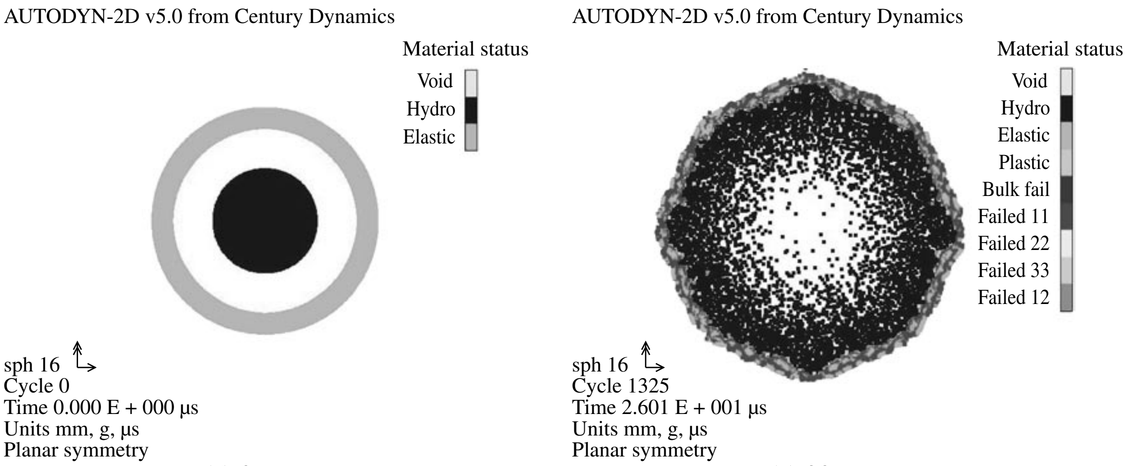


Fig. 6 Experimental wall radii for smooth cylinders.

3. Calculation

Calculation in 2 dimensions was carried out in order to obtain more detail data on expansion and deformation under high energy. The calculation results were compared with the observation results. AUTODYN-2D was used for the simulation. AL5083H116 was selected as Aluminum based alloy. Fracture analysis was made by SPH method. In simulation, the cross-section of the test cylinder consisted of 0.2 mm particles and flocculated the particle into the cylindrical shape.

Figure 7(a) shows the calculation result on PETN ϕ =16 mm. We found that the size of fragments became smaller and the number of one increased when the diameter of PETN column became larger. These trends agree with the experimental result. Figure 8 shows the calculation result on the history of expansion of outer diameter of the



(a) 0 µs (a) 30 µs

Fig. 7 Numerically expanding and fragmenting smooth cylinder (PETN ϕ =16 mm).

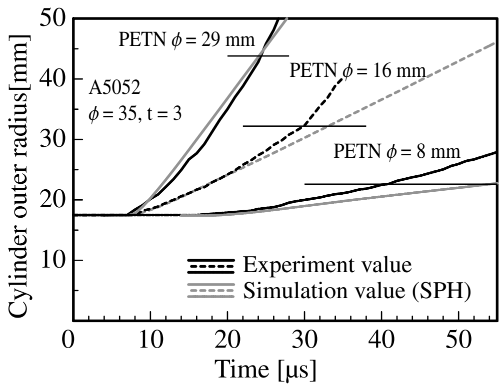


Fig. 8 Numerical and experimental wall radii for smooth cylinders.

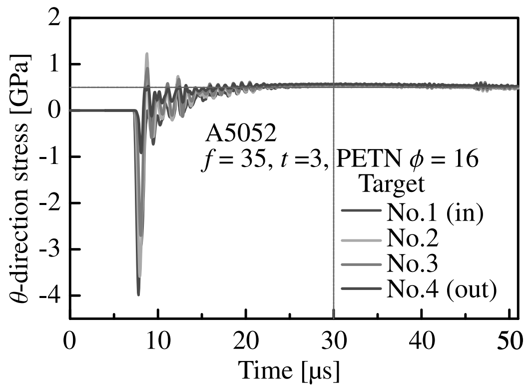


Fig. 9 Numerical time-history of circumferential stresses in the wall of smooth cylinder. (PETN ϕ =16 mm)

test cylinder. These data agree with the experimental data except for the case that the diameter of PETN column is small. The reason of this exception is as follows. When the diameter of PETN column is small, in SPH method the number of particle is small in the cylinder. The particle density becomes low and the distance between particles spreads at the time of explosion.

Stress analysis in the part of thickness of the test cylinder was made by FDM. In the part of the cylinder Lagrange grid was used and in the other part Euler grid. Figure 9 shows the results on PETN ϕ =16 mm. In this figure inner side was labeled as No.1 and outer side as No. 4. We found that the time when breaking stress approached to 0.5 GPa was different from breaking time. From this result, the breaking criteria were found to be not only stress.

4. Examination of Grady model

Typical recovered fragments are shown in Fig. 3. It is seen that fracture of the cylinder portion is predominantly along elongated strips, with the fracture parallel to the axis. Most of the fragments are 3-6 times longer than they are wide, and shear fracture appears to be the dominant mechanism. Fragment size statistics of width S, thickness t_f at the central location for every fragment are determined except those of cylinder edges and very small ones, and furthermore the experimental fragmentation energy Γ (= $\rho \dot{\varepsilon}^2 S^3$ / 24, ρ: density) proposed by Grady[6] is calculated using such data.

The fragmentation energy was determined by Grady model from the measuring size of fragments seen in Fig. 3 and the parameters in Table1. The histograms of fragmentation energy on PETN ϕ =29mm, 16mm, 8mm were compared and examined (Fig. 10). The peak and average of fragment energy was different to each the diameter of PETN column, because the distribution of fragment size was different. Further the lack of the sampling number was concerned with these results probably. We can found that there was specific fragmentation energy to each the diameter of PETN column and the improvement of Grady model was needed in order to apply to the prevent case.

Table 1 Strain rate obtained from Breakup times and expansion history.

PETN ϕ [mm]	Breakup times [μs]	Expansion velocity [m s^{-1}]	Strain rate [$\times 10^4$ s^{-1}]
29	24	2430	5.56
16	30	984	3.05
8	40	281	1.26

5. Conclusions

In this study, we made the experiment of the expansion of cylindrical material. The conclusions are as follows.

- Cylindrically diverging detonation waves generated in PETN using a wire-explosion technique are applied successfully to expand metallic cylinders of aluminum (A5052) axially almost uniformly at very high strain rates of above 104 s^{-1} with variations of explosive diameters and cylinder wall thicknesses.
- Rapid expansion and following fracture initiation behavior are observed and examined using high speed camera (IMACON) and hydro codes (Autodyn2D).

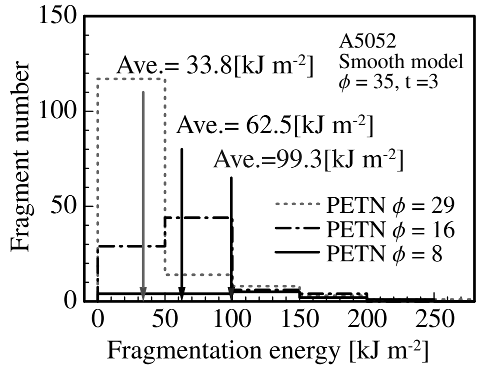


Fig. 10 The comparison of fragmentation energy in each the diameter of PETN column.

- It seems that the breaking criteria of aluminum based alloy is concerned with not only circumferential direction stress but also retention time.
- The improvement of Grady model is needed in order to apply to A5052.

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爆発破砕解析のための破砕モデルの検討
(アルミ円管を用いた爆発破砕実験)

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ロケットや衛星，高エネルギ機器の爆発事故等が発生すると，周辺環境に対して甚大な被害を及ぼすことになる。そのため，超高速ひずみ速度下における膨張変形･破壊挙動およびその分裂形態を把握し，爆発事故評価に適するための爆発破砕モデルの開発が必要である。本論文では，中心軸銅細線一斉起爆技術とペンスリットを用い，アルミニウム合金(A5052)円筒内部に円筒状発散爆轟波を生成させ，爆発破砕実験を行った。実験においては，超高速度カメラを用いた撮影と破片回収を行っている。その上で Autodyn 2Dを用いた数値解析を行い，実験結果と比較を行っている。それらの結果を用いて半解析的モデルとして使われている Gradyモデルについて検討を行っている。

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