Energy Output Efficiency of Shielded Mild Detonation Cord in Cylinder Structures

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Abstract. Expanding tube separation device is a commonly used linear separation device, whose energy resource is a shielded mild detonation cord (SMDC). In this research, the SMDC is a mild detonation cord sheathed in flat polyethylene. Two experiments were achieved to discuss the energy output efficiency of the SMDC. In the first experiment, the SMDC was inserted into 1060 aluminum cylinder directly. While in the other experiment, the SMDC was insert into aluminum cylinder after contained within a flat steel tube. The velocity and displacement of the characteristic points on the outer surface of the aluminum cylinder during explosion were measured by photonic Doppler velocimetry (PDV). The simulation results with LS-DYNA fluid-solid coupling algorithm correspond well with the experimental results. According to the simulation analysis, the distribution of total energy of explosives were obtained. The plastic strain energy of the aluminum cylinder corresponds to the ability of the SMDC to do external work. The result shows that, 39.3% of the total energy in the explosive is output to aluminum cylinder with SMDC acting on it directly, while the energy output efficiency turns to 20.8% after passing through the flat tube.

1. Introduction

Expanding tube separation device is a typical linear separation device. The function of the separating device is to supply reliably connection of the structures before separated. Moreover, when the separation is required, the specified part of the separating device is destroyed to achieve the separation of connecting structures. Therefore, it is a significant part for the whole system [1, 2]. The shielded mild detonation cord (SMDC) in this research is a mild detonation cord coated with polyethylene in flat ribbon shape, that is the energy resource of the device. During the working process, high energy of the SMDC is fast released. The energy of the explosive is transmitted to the flat tube through the polyethylene, then transmitted to external structure. To study the mechanism of this structure for a better guidance in actual structural design, it is necessary to analyse the energy output efficiency of this kind of SMDC.

However, the quantity of explosive energy cannot be measured directly. It is usually converted to other energy forms. Traditional explosive energy testing methods including lead-cast, blasting funnel, ballistic mortar, underwater explosion and detonation cylinder test [3-9], which convert the explosive energy to kinetic energy, plastic strain energy, or bubble energy. For theoretical analysis, classical Gurney formula is used to describe energy distribution of explosive acting on regular symmetrical structures, such as cylindrical specimens and plates [10]. However, for expanding tube assemblies, the flat structure changes the energy distribution of the explosive in the circumferential direction, which is more complicated. Until recently, various researches are presented on the transfer and distribution of explosive energy. Rao studied the explosive energy output characteristics of aluminum-containing...
explosives in water, confined space and air [11]. Feng studied the output characteristics of explosive energy in rocks, the energy of explosion shock waves accounts for about 40%, and the energy generated by explosive gases accounts for about 60% [12]. Zhao studied the characteristics and energy distribution of blast waves in concrete by experiments [13]. Cao used cylinder experiment to measure the work ability of the mild detonating fuse [14]. In most of these studies, the explosives are applied to the object directly. For SMDC, the energy of the explosive energy is transmitted outside through polyethylene, and the energy transmission efficiency is unclear.

In this paper, deformation cylinder test is used to measure the energy output efficiency of the SMDC in cylinder structures. The experiment is designed in the next section. Then simulation method is introduced in Section 3. Experimental and simulation results are compared and analysed in Section 4. The paper is then concluded in Section 5.

2. Experiment design
Considering 1060 aluminum has well plastic properties, it is selected as the material of the outer cylinder to absorb the output energy of the SMDC in this paper. The inner hole matches with the SMDC and the flat tube, respectively. The expansion velocity and displacement of the four feature points on the middle section of the cylinder were measured by a photonic Doppler velocimetry (PDV). The experimental device was composed of a bottom plate, a top cover and four screws. Four PDV probe brackets were mounted on the bottom plate. Adjusting the brackets, laser outputs from the fiber optic probes can be aligned with the measured points. The specimens were fixed in the middle of the device by clamps. The combination of experimental specimens includes two types. In condition 1, the SMDC is directly penetrated into the aluminum cylinder. In condition 2, the SMDC is penetrated into the aluminum cylinder after being presented in a flat steel tube. Experiment device and specimens are showed in Figure 1.

3. Simulation method
3.1. Geometry and finite element models
The structure was modelled by Hypermesh. The 10 mm in the middle of the structure were selected as separate parts to avoid the influence from the boundaries in analysing energy output efficiency. The aluminum cylinder and the flat tube were meshed as lagrange elements, while the air, polyethylene, lead and explosive were euler elements. In the Ls-dyna fluid-solid coupling analysis, the lagrange and euler meshes can overlap each other, therefore, the air mesh and the aluminum cylinder mesh were overlapped. Two kinds of finite element mesh models are showed in Figure 2.
3.2. Material models
The relevant material parameters of the simulation were referred to the existing studies [15-18]. The material model of the explosive (RDX) was Mat high explosive burn and the JWL equation of state was set, wherein the explosive velocity of the explosive was 7344 m/s to the average value provided by the explosive's manufacturer. The air and lead were set to the Mat null model. The lead used the Gruneisen equation of state, while the air was the gamma criterion equation. The polyethylene used the Mat piecewise linear plasticity material model, the flat steel tube and 1060 aluminum cylinder used the Mat power law plasticity material model as an elastoplastic model considering strain hardening.

4. Results analysis
4.1. Comparison of simulation and experimental results
In the simulations with condition 1 at first, the simulation results were somewhat different from the experimental ones. In terms of material parameters, parameters for explosive, lead, polyethylene and flat tube selected have been verified in previous researches, therefore, they are suitable for simulation analysis with explosive load [15-17]. Reference [18] indicates that 1060 aluminum is strain hardening and sensitive to strain rate and temperature, but the Mat power law plasticity material model for 1060 aluminum in the keywords of Ls-dyna only considered the strain hardening and strain rate effects. A large amount of heat released during the explosion loading process, which would change the temperature of the 1060 aluminum. Meanwhile, considering the different loading method or other uncertain factors from the reference which may cause deviation in material parameters. In the later simulation, a coefficient $\eta$ was introduced to amend the constitutive equation of 1060 aluminum material. In the material parameter setting of the keywords, $\eta$ was introduced by multiplying to the strength coefficient. A large number of simulation analysis and comparisons showed that when $\eta$ is 0.686, the simulation results agree well with the experimental results. There were three experiments for each condition. Point 1 and 3 are symmetric points, so as point 2 and 4. The symmetric points results were consistent.

The experimental and simulation results are showed in Figure 3. The velocity of point 1 and 3 on the aluminum cylinder drops faster after reaching the extreme value, and increases in the reverse direction. While expand time of point 2 and 4 is much longer. After the velocity of point 2 and 4 drops to zero, it gradually stabilized after a small fluctuation. In the corresponding displacement curve, when the expansion displacement of point 1 and 3 reach the extreme value, the displacement of point 2 and 4 is still increasing. Due to the expansion traction of point 2 and 4, point 1 and 3 are contracted inward,
which indicates that the SMDC can do more work in the short axis. After about 80 μs, the velocity of the four points began to slowly approach to the final stable value.

![Velocity and displacement curves of point 1 and 3](image1)

![Velocity and displacement curves of point 2 and 4](image2)

**Figure. 3** Comparison of simulation and experimental results of the SMDC acting on the aluminum cylinder directly.

Keeping all parameters unchanged, a model of the flat tube was added to obtain another simulation result. The experimental and simulation results are showed in Figure 4. Due to the addition of the flat tube, the amplitudes of velocity and displacement are reduced. Compared with the final expanding of point 1 and 3 in condition 1, they are contracted in condition 2. After the restriction of the flat tube, the energy was output more concentrated on the direction of short axis of the SMDC.
Figure 4. Comparison of simulation and experimental results of SMDC acting on aluminum cylinder after passing through a flat tube.

The aluminum cylinders were cut at the middle section of the longitudinal direction after the experiment. The final states of the experiment and simulation results are showed in Figure 5. The inner holes are obviously enlarged, and a large local plastic deformation occurs. After the flat tube was applied, the amount of expansion was reduced.

Figure 5. Sectional view of aluminium cylinders under two working conditions:
(a) condition 1, (b) condition 2.
4.2. Energy output results

The energy distribution process was obtained by simulation analysis. The energy history of each structure in the middle parts of the specimen were divided by the total energy of the part of the explosive to get the energy output efficiency, as shown in Figure 6.

![Figure 6](image)

**Figure 6.** Energy histories of each structure under two conditions: (a) condition 1, (b) condition 2.

When the SMDC acts on the aluminium cylinder directly, the plastic stain energy of the aluminum cylinder accounts for 39.3% of the total energy of the explosive. In addition, the polyethylene and air accounts for 12.9% and 14.5% of the total energy, respectively. When the SMDC acts on the aluminium cylinder through the flat tube, the plastic stain energy of aluminum cylinder is 20.8%, the plastic stain energy of the flat tube is 8.1%, the polyethylene is 14.6%, and the air is 14.7%. For both conditions, the final energy of lead approach to zero. For condition 2, after the flat tube added, more interfaces were introduced, the explosion shock wave was attenuated. Besides, the flat tube consumed part of the energy, so the energy finally transmitted to the outer aluminum cylinder was reduced.

5. Conclusions

In this paper, the energy output efficiency of the SMDC is studied through experiments and simulation analysis. The velocity and displacement of the characteristic points on the outer surface of the aluminum cylinder during explosion were measured by PDV. And energy distribution was researched by simulations. The result shows that, 39.3% of the total energy in the explosive is output to aluminum cylinder with SMDC acting on it directly, while the energy output efficiency turns to 20.8% after passing through the flat tube. It can be seen from the deformation form of the aluminum cylinder that the SMDC does work in directionally way. That is, the energy is output more concentrated on the direction of short axis of the SMDC. This paper supplies a guidance for separation device design.

6. References

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