Dynamic fracture of the AISI 1045 steel cylinders under internal blast loading

Y Ma, Y He*, CT Wang*, Y He, Z P Guo and X B Hu.

ZNDY of Ministerial Key Laboratory, Nanjing University of Science and Technology, Nanjing 210094, China.

Email: mayue68@njust.edu.cn (Y Ma).

Abstract. Dynamic fracture failure of the AISI 1045 steel cylinders with variable depth grooves under internal blast loading was investigated. Lateral and longitudinal grooves were curved on the wall of steel cylinders along with radial direction. All grooves have a V-shape with 20° angle. After blast, the morphology of fragments recovered by multi-layer wooden planks showed relative consistency. Microstructure in cross and longitudinal section of the fragments was examined by scanning electron microscope (SEM). The microstructure observation suggested that there were some undeveloped shear bands and the dynamic fracture modes were similar in the all tests but the different fracture mode in two directions. Relevant numerical simulation by LS-DYNA were carried out to analyze the expanding and fracture process of cylinders under internal blast loading. Numerical results have acceptable agreement with experiment results. The mass loss rate of shell after explosion is negatively correlated with the depth of grooves.

1. Introduction

The dynamic fracture failure of explosive cylinder shell is very important for the design of warhead. Under detonation loading, the inner wall of the cylinder shell will be affected by high temperature and high pressure which will quickly conduct to the whole shell wall thickness. The whole shell expands and breaks rapidly under the conditions of high temperature, high pressure, high strain and high strain rate, and the process is short and intense. So it's quite complicated. So far, scholars have focused on fracture mechanism, fracture strain, fracture stress, fracture size and fracture velocity.

In 1943, Gurney [1] estimated the rate of fragmentation under detonation loading based on the law of energy conservation, a hypothesis that has been widely used to estimate fragmentation velocity. However, the velocity of fragments estimated by this method is equal for all fragments due to the assumption of instantaneous detonation and ignoring the effect of shock wave. In 1944, Taylor [2] proposed the Taylor criterion, which can predict the fracture strain of shell breakage. It was considered that when the shell fractured, the crack direction was radial along the shell and the crack generated on the outer surface and gradually extended to the inner wall. When the crack penetrates the wall thickness, the shell breaks. R. L. Martineau et al. [3] conducted two sets of experiments with the same
inner diameter and different wall thickness of the shell, and concluded that during the expansion of the shell, when the strain reached 150%, the multiple plastic instability appeared on the surface of the shell in a quasi-periodic mode, followed by shear localization, resulting in fracture. T. Hiroe et al [4]. designed a series of cylinder implosion tests, taking into account the impact of shell material, wall thickness grooves, driving explosive diameter and detonation point on shell breakage, and using the SPH method for simulation and test verification. The experiments and simulations showed that the smaller the shell wall thickness and the more explosives led to the smaller size of the fragments. The effect of grooves on shell deformation is inapparent at high strain rate, but significant at low strain rate. In addition, the impact of the location of the detonation point is not significant but it is also a factor that must be considered. D.M. Goto et al [5]. conducted implosion cylinder tests on AerMet 100 alloy and AISI1018 steel respectively, determined the fracture strain under uniaxial stress state and plane strain state, and obtained the microstructure change of the material under detonation loading through recovery analysis of the generated fragments. M. Z. Liang, Xiang Yu Li et al [6-9]. conducted a series of experiments on internal and external crisscross groove rings, and obtained the fracture mode of groove rings. PENG zheng-wu et al [10]. conducted numerical simulation analysis on the grooving shell and obtained the law of the formation of fragments by grooving parameters. Mingtao Liu [11-12] focused on the adiabatic shear fracture mechanism of cylindrical shell driven by detonation, and used the numerical simulation method to reproduce the process from expansion to fracture of cylindrical shell, which was in good agreement with the experimental results. DUAN Yan [13] designed and verified an example to conduct numerical simulation of the fracture process of the pre-grooving shell under detonation loading. It was believed that the influence of the top Angle of the grooving section on the initial velocity of fragments would gradually increase with the decrease of the groove depth, and the best effect would be achieved when the top angle was 90° and the fracture time depended on the groove depth. Jianjun Zhu [14] used 40CrMnSB steel with different heat treatment processes to conduct implosion shell test, and obtained the influence of tempering temperature on shell fracture and used statistical theory to fit the fracture distribution. ZHANG gao-feng et al [15]. carried out experiments on internal and external symmetrical grooves and treated the recovered fragments, and obtained the mass loss rate of the fragments. Xining Wang et al. [16] conducted experiments on imploding shells of three metals, and used high-speed photography to record the process of shell expansion to crushing, and PDV to record the breaking speed. The material plasticity has a great influence on the rupture radius of the cylinder. Although a great deal of studies have been made on the fracture mechanism, there were still few studies on the fracture mode with both circumferential and axial fractures of internal and external symmetrical grooves.

In this paper, AISI 45 steel is used as shell material, and v-shaped groove is carved symmetrically inside and outside, and the groove angle is 20 degrees. The circumferential and axial fracture processes of the shell under internal blast loading are studied.

2. Experiment

2.1. Experiment set-up

The specimen used in the test was made from AISI45 steel without any heat treatment. Its inner diameter, wall thickness, height is 62mm, 10mm, 120mm, respectively. V-shaped grooves are symmetrically carved on the inner and outer walls of the shell. The angle of the groove is 20 degrees. The angle between the two adjacent grooves in the circumferential direction is 18 degrees, and the distance between the two adjacent grooves in the axial direction is 10mm. The design drawing of one specimen is showed in figure 1. In order to distinguish the direction of the recovered fragments, an axial line was drawn on a list of pre-controlled fragment. The physical specimens used in the test are shown in figure 2a. The high energy explosive used in the test was powder pressed and formed, with the charge diameter of 60mm and the length of 60mm. During the test, the two charge columns were
bonded together through shellac to serve as the driving charge column.

![Design drawing (notches depth =1 mm): (a) vertical view; (b) front-sectional view.](image)

**Figure 1.** Design drawing (notches depth =1 mm): (a) vertical view; (b) front-sectional view.

![Actural experimental arrangement: (a). The physical specimens used in the test; (b). Image of the experimental set-up.](image)

**Figure 2.** Actural experimental arrangement: (a). The physical specimens used in the test; (b). Image of the experimental set-up.

In the test, the end-point center detonation mode was adopted. The shell was placed vertically on the surface of cement pier, surrounded by wood boards at a distance of 1.5m. The boards are 20mm thick, with 15 layers in each direction. Considering that the velocity of fragments varied at different positions along the axial direction of the shell, the velocity of fragments was not measured in the test. The experimental arrangement is shown in figure 2b.

### 2.2. Experiment results

After blast, fragments were recovered from the wood boards. The recovered fragments are shown in the figure 3a-e. According to the test results, the in-completely fractured fragments were observed in the shell test with groove depth of 3.5mm and the number increased significantly groove depth reduced to 3mm. Less fragments were recovered for the shell with groove depth of 2.5mm, as the kinetic energy of in-completely fractured fragments was large enough to penetrate the wood boards. As the axial force is smaller than radial force during blast, the observation of those fragments showed that the connected direction was axial adhesion. On the axial crack of the pre-control groove, it was observed that the dominating fracture mode was tensile-shear mixed fracture.
Figure 3. Recovered fragments with variable grooves depth: (a) grooves depth=2.5mm; (b) grooves depth=3.0mm; (c) grooves depth=3.5mm; (d) grooves depth=4.0mm; (e) grooves depth=4.5mm.

Defining that the ideal fragment mass is the total mass of the shell divided by the number of pre-control fragments, the mass loss rate of fragments after explosive loading of the shell in various experiment was obtained under the condition that the recovered fragments were weighed. The relationship between the mass loss rate and the depth of notches is shown in the figure 4. The mass loss rate of the shell increases with increasing of the groove depth. Contrary to the results of Ref [11], because the shell used in this study was symmetrically grooved. Under the implosion loading, cracks are generated not only in the internal groove but also in the external groove. When the crack between the two grooves passes through, the metal between the cracks produces a small mass of debris. As the depth of the slot increases, the distance between the two slots becomes smaller and smaller, and the greater the probability of penetration between the slots, the more mass is lost.

Figure 4. The mass loss rate with variable groove depth.

3. Simulation

3.1. Finite element model

Usually, there are three methods in numerical simulation of detonation driving the Lagrangian common node method, the sliding detonation driving method and the arbitrary Lagrangian Eulerian (ALE) method. The Lagrangian common node method defines both the explosive and the metal shell as the Lagrangian grid. The common node at the contact point of the two is used to transfer the force between the explosive and the shell. The sliding detonation driving method is to establish the slip contact between the two through transfer contact force. ALE method adopts coupling mechanism for
modelling Fluid-Structure Interaction (FSI). The former two adopt the Lagrange method, since the explosive element needs to be deleted due to the large deformation of the explosive element at the beginning of the calculation, so the effect of gas products on fragments cannot be accurately described. In addition, the slip detonation drive method requires complete contact between the shell and the explosive node to node, which is inconsistent with this test scheme. Therefore, ALE method was used to simulate the shell deformation driven by detonation.

Based on the above analysis, commercial CAE software LS-DYNA was used for numerical simulation. The simulation model is shown in the figure 5. The configuration parameters assembly were consistent with the test, the outer diameter of air region is 140mm. The explosive and the air are divided into euler grids with common nodes and multi-material elements. The shell is divided into lagrangian grids. FSI keyword *CONSTRAINED LAGRANGE IN SOLID was used to define the interaction between lagrangian grid and euler grid. Since only one lagrangian body, the shell, exists in the simulation model, the global contact was defined as automatic single-surface contact to simplify the calculation. The initiation detonation mode is single point at one end, as shown in the figure 5.

3.2. Material model and state equation

The shell material is AISI45 steel, which is described by Johnson-Cook (JC) material model and Gruneisen state equation. The expression of JC model is shown in equation (1). The model comprehensively considers the effects of strain hardening, strain rate effect and thermal softening on materials, which can well simulate the dynamic response of materials under explosive loading. Cumulative damage criterion was used in JC model of LS-DYNA. When the damage parameter D of one node in the material reaches the value of 1, then it is considered to be failed, and will be deleted. The damage parameter D is defined in equation (2). According to equation (2), it is clear that the damage parameter generally considers the effect of the stress condition and temperature on element damage, so the fracture of grooving shell under detonation loading can be accurately simulated. The

![Graph simulation model](image)
JC model parameters of AISI45 steel are shown in table 1 [17].

\[ \sigma_y = \left[ A + B (\varepsilon^p_e)^n \right] \left[ 1 + C \ln \dot{\varepsilon}^* \right] \left( 1 - T^{*m} \right) \]  \hspace{1cm} (1)

Where A, B, n, C, m are the material parameters, \( \varepsilon^p_e \) is effective plastic strain, \( \dot{\varepsilon}^* = \varepsilon^p_e / \dot{\varepsilon}_0 \) is dimensionless effective plastic strain rate, \( \dot{\varepsilon}_0 \) is quasi-static threshold strain rate, \( T^{*m} = (T - T_{room})/(T_{melt} - T_{room}) \) is homologous temperature.

\[ D = \sum \frac{\Delta p^p}{\dot{\varepsilon}^c} \]  \hspace{1cm} (2)

Where \( \varepsilon^c = [D_1 + D_2 \exp D_3 \sigma^*] [1 + D_4 \ln \dot{\varepsilon}^*] [1 + D_5 T^*] \) is the strain at fracture.

The detonation of explosive, with high explosive detonation model (*MAT_HIGH_EXPLOSIVE_BURN), is described by JWL equation. Its parameter values are shown in table 2 [18].

Air with null materials (*MAT_NULL) model is described by linear polynomial equation of state (*EOS_LINEAR_POLYNOMIAL). Its parameter values are shown in table 3 [17].

**Table 1.** The parameters of Johnson-Cook (JC) model material of AISI 45 steel.

| \( \rho_0 \) | A/(MPa) | B/(MPa) | n | C | m | D_{1} | D_{2} | D_{3} | D_{4} | \( \dot{\varepsilon}_0 \) | S_{I} | \( \gamma_{0} \) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| \( g \cdot \text{cm}^{-3} \) | \( \text{kg/m}^3 \) | \( \text{km} \cdot \text{s}^{-1} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) | \( \text{GPa} \) |
| 7.85 | 507 | 320 | 0.28 | 0.064 | 1.06 | 0.10 | 0.76 | 1.57 | 0.005 | -0.84 | 4.569 | 1.49 | 2.17 |

**Table 2.** The parameters of high explosive.

| \( \rho_0 \) | \( \text{g/cm}^{3} \) | \( D \) | \( \text{m/s}^{-1} \) | \( P_0 \) | A/GPa | B/GPa | R_{1} | R_{2} | \omega | A/GPa | \sigma_{y}/GPa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.78 | 8425 | 29.7 | 854.5 | 20.49 | 4.6 | 1.35 | 0.25 | 3.54 | 0.2 |

**Table 3.** The parameters of air.

| \( \rho_0 \) | \( \text{g/cm}^{3} \) | C_{6} | C_{7} | C_{8} | C_{9} | C_{10} | C_{11} | C_{12} | C_{13} | C_{14} | C_{15} | C_{16} |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00129 | 0 | 0 | 0 | 0 | 0.4 | 0.4 | 0 |

3.3. Numerical simulation results and analysis

3.3.1. Fragmentation dispersion characteristics. Fragmentation dispersion along axial and circumferential direction. The diagram of dispersion is shown in the figure 6. The axial dispersion angle is defined as the included angle between the direction of fragmentation velocity and the normal direction outside the shell. In order to simplify the calculation, the location of the center of the ideal pre-controlled fragment is obtained in both the velocity direction of the fragment and the normal direction of the outer shell. The dispersion field of fragments at different time can be obtained by numerical simulation, as shown in figure 7 (an example of the simulation result of 4.5 groove depth). It was obvious that the fragments at the position 3/4 of the shell length have the largest velocity. By comparing the dispersion field of fragments with different depth of notches, it is concluded that the influence of notch depth on fragmentation dispersion field was not significant.
Figure 6. The diagram of dispersion: (a) normal; (b) fragment velocity direction; (c) axial dispersion angle; (d) circumferential angle.

Figure 7. The diagram of dispersion field from numerical simulation: (a) front view; (b) isometric view.

It is observed from the fragment dispersion field that the fragments fly uniformly in the circumferential direction, so one column was extracted for analysis. The distribution of fragmentation velocity along the axial direction is shown in the figure 8. The effect of groove depth on the initial velocity of fragmentation is small and the regularity fragmentation velocity with the axial distance is consistent. Due to the effect of edge sparse effect, as shown in the figure 9, the velocity of fragments at both ends is smaller. According to the formula of Gurney, the ratio of charge mass to shell mass is an important factor affecting the initial velocity of fragments in the case of consistent wall materials.

Figure 8. Fragment velocity along the axial direction.

Figure 9. Sparse effect at both ends from simulation: (a) 18us; (b) 30us; (c) 45us.
The variation of circumferential angle of fragmentation with depth of groove is shown in figure 10. As shown in the figure, the circumferential angle first increases and then decreases with the increase of the groove depth, and its volatility decreases and gradually stabilizes with the increase of the groove depth. The axial dispersion angle of fragments formed by different shells varies with the axial distance, as shown in the figure 11. It is shown in the figure that the axial dispersion law of fragments is highly consistent, concentrated between -30° and 24°. Due to the influence of rarefaction wave at the detonation end, the first four rows of fragments fly in the opposite direction.

3.3.2. Dynamic rupture. The full-model simulation can see the expansion and fracture of the shell in the circumferential and axial direction. According to the simulation results, the force of the shell under detonation loading can be obtained, which facilitates the analysis of the fracture mode of the shell. The shell expansion process was analyzed with the depth of the groove being 4.5mm. The expansion of the shell at different times is shown in the figure 12. Because the shell is a complete cylinder in the radial direction, it is subjected to great radial detonation pressure when the shell expands. In the axial direction, the two ends of the shell are not closed, so the axial force is not large. By combining the forces in the axial and radial directions, it is concluded that the circumferential fracture of fragments precedes the axial fracture, as shown in figure 12 (d).

4. Discussion
According to Ref [19], there are mainly two fracture modes: shear fracture and tension-shear mixed fracture mode. When the thickness of shell wall is small, shear fracture is the dominating fracture
mode [7]. The specimens used in this study is a symmetrical grooving shell, the actual wall thickness can be considered as the distance between the notch tips. Therefore, when the depth of the groove is 4.5mm, the actual wall thickness is 1mm. According to this simplification, it is obvious that, with the decrease of groove depth, the wall thickness becomes larger, and the shell fracture mode transitions from shear fracture to tension-shear fracture. It is assumed that here exists a critical thickness. When the thickness of the shell is less than this value, the fracture mode of the shell is pure shear fracture. When the thickness of the shell is greater than this value, the fracture mode of the shell is tension-shear mixed fracture.

After polishing the recovered fragments, SEM was used for metallographic observation. Typical metallographic images are shown in the figure 13 and figure 16. Figure 13 shows the microstructure of the cross section. When observed in this direction, the circumferential crack section of the fragment can be observed. The inner surface of the shell is subjected to the detonation pressure and the high temperature generated by the explosion. As shown in the figure 13(a) (b), at the corner of the inner surface of the fragment, the grains are stretched. The detonation wave then transfers the pressure to the bottom of the inner groove of the shell, where the internal initial crack is generated, due to stress concentration. As shown in the figure 13(c) (d) (e) (f), shear cracks and shear bands can be observed. By comparing the cracks on the left and right sides of the circumferential fracture, it is found that when the circumferential fracture occurs, the forces on the two sides of the fracture are similar, so the cracks generated are nearly identical. Compared with the simulation results: at 2μs, the inner surface of the fragment began to bear detonation pressure: at 4μs, stress concentration occurred at the bottom of internal groove of the shell; at 6μs, the stress transferred to the external groove, which was basically consistent with the above reasoning, as shown in figure 14.

![Figure 13](image-url)

Figure 13. The metallographic image of the cross section (groove depth =3.5mm): (a) inner corner of left side; (b) inner corner of right side; (c) (d)the shear crack of left side; (e); (f) the shear band of left side.
The fragment was cutted along longitudinal direction and polished, the crack section of axial fracture can be observed, as shown in the figure 16. There were grain deformation in different directions at the inner surface corner of the groove, as shown in figure 16(a) (b). The grain deformation direction at the corner on the right of the fragment (figure16 (b)) is from the inside of the fragment to the outside. Based on the above analysis, Based on the above analysis, it can be known that this is caused by the detonation pressure. However, the grain deformation on the left side of the fragment (figure16 (a)) is larger and the deformation direction is contrary to right. So the deformation is obviously not caused by detonation pressure. Moreover, the grain on the right edge is consistent with the matrix organization, which is speculated thought the groove surface. The macroscopic crack (figure16 (e)), whose root exists shear localization, can be observed in the center of the right side of fragment, indicating that this crack is a shear crack. The obvious grain tensile deformation, as shown in figure16 (d)) can be observed near the outer surface of the fragment at the right side, suggesting that it is tensile fracture. The details of the crack on the left side near the inner surface are shown in figure 16 (c). It can be seen that the inside of the crack is different from the shear crack on the right side, which proves that the crack is not a shear crack. And according to the grain direction and elongation at the left corner of inner surface, this is typical character of tensile fracture. By comparing the simulation results, as shown in the figure 15, it is concluded that at 2μs after explosion, the inner surface of the broken shell begins to be affected by detonation pressure and deforms; at 4μs, stress concentration occurs at the bottom of the internal groove near the end of the detonation point, and the initial deformation expands downward; at 6μs, the external groove is affected by deformation and stress concentration occurs. Due to adopt the endpoint center detonating, on the edge of the initiating end with the sparse effect, its detonation was inadequate development, so the pressure was lower than intermediate position of shell. Shell expansion radius at the same time were different, as shown in the figure 12. Meanwhile, tensile cracks occurs at the bottom of the external grooves, as shown in figure 17.
Figure 16. The metallographic image of the longitudinal section (groove depth =2.5mm): (a) inner corner of left side; (b) inner corner of right side; (c) the crack of left side; (d) the deformation of external corner of right side; (e) shear crack.

Figure 17. Incompletely fractured fragment with internal and external cracks: (a) axial cracks of the internal grooves; (b) axial cracks of the external grooves.

5. Conclusion

Through the explosion drive test of the shell with various groove depth, some fragments were recovered with wood board. SEM was used to examine transverse and longitudinal microstructure on the recovered fragments. The fracture mode of the shell in circumferential and axial expansion was analyzed. The corresponding experiments were simulated by LS-DYNA software, and the circumferential angle and axial dispersion angle of the fragments were obtained. The three-dimensional simulation clearly reproduced the expansion and fracture process of the shell, which greatly promoted the analysis of the test results.

Based on the above work, the following conclusions are drawn:

(1) The circumferential fracture mode of the shell with internal and external grooves is mainly tensile-shear mixed fracture mode, and the shear crack starts in the inner wall and the tensile crack starts in the outer wall. The fracture modes on both sides of the circumferential rupture are the same;

(2) The axial fracture mode of the shell with internal and external grooves is mainly tensile-shear mixed fracture mode, but the fracture mode on both sides of the fragments is not same in the axial direction. The side near the starting point end under detonation pressure germinates the initial shear crack at the bottom of the internal groove, then tensile crack at the bottom of the external groove initiates. On the other side, it is tensile fracture near the inside of the fragment;

(3) The mass loss rate of the shell is positively correlated with the groove depth.
References

[1] R W Gurney 1943 The initial velocities of fragments from bombs shell and grenades BRL Report No. 405 Army Ballistic Research Laboratory MD USA.
[2] G I Taylor 1963 Sci. Papers Cambridge University Press London 387–90
[3] R L Martineau, C A Experimental Mech 40(2) 219–25
[4] T Hiroe, K Fujiwara, H Hata and H Takahashi 2008 Int. Journal of Impact Engineering 35 1578-86
[5] D M Goto, R Becker, T J Orzechowski, H K Springer, A J Sunwoo and C K Syn 2008 Int. Journal of Impact Engineering 35(12) 1547-56
[6] M Z Liang, X Y Li and F Y Lu 2015 Theoretical and Applied Fracture Mech. 77 50–8.
[7] X Y Li, M Z Liang, M F Wang, G X Lu and F Y Lu 2014 Propellants Explos. Pyrotech 39 723-32
[8] M Z Liang, X Y Li, J G Qin and F Y Lu 2013 Rev. Sci. Instrum. 84(6) 065114
[9] M Z Liang, X Y Li and F Y Lu 2016 Int. Journal of Applied Mech. 08(1) 1650003
[10] Z W Peng, Q Zhang, X M Wang, W B Li and P Liu 2013 Initiators & Pyrotechnics 01 17-20
[11] M T Liu, Y C Li, H B Hu and X Z Hu 2014 Modelling and Simulation in Materials Sci. and Engineering 22(1) 015005
[12] M T Liu, G W Ren, C Fang, T G Tang, X Y Wang and H B Hu 2017 Int. Journal of Impact Engineering 109 240-52
[13] Y Duan, X X Zhao and T B Ma 2014 Transactions of Beijing Institute of Technology 34(s1) 53-6
[14] J J Zhu, W B Li, X M Wang and W B Li 2017 Int. Journal of Impact Engineering 107 38-46
[15] G F Zhang, X D Li, L W Zhou and L Y Ma 2018 ACTA ARMAMENTARII 39(20) 254-60.
[16] X Y Wang, X S Kong, C Zheng and W G Wu 2018 Defence Technology 14 578-84
[17] Q Ling, Y He and Y He 2017 Journal of Vibration and Shock 36(3) 234-41
[18] Y C Wang, J Wang and K Wang 2013 ORDNANCE MATERIAL SCI. AND ENGINEERING 36(2) 37-40
[19] N F Mott 1947 NATO ASI Series, Series C: Mathematical and Physical Sciences 189(1) 300–8