Research Article

Mechanism of Microscopic Fracture of Typical Shell Steel under Impact Loading

Chuan Zhao,¹ Shushan Wang,¹ Cean Guo,² Yuhui Sun,¹ Xuncheng Guo,^{1,3} and Feng Ma¹

¹State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

²Shenyang Ligong University, Shenyang 110159, China

³Xi'an Modern Control Research Institute, Xi'an 710065, China

Correspondence should be addressed to Feng Ma; kang@bit.edu.cn

Received 1 November 2021; Revised 15 January 2022; Accepted 2 February 2022; Published 23 February 2022

Academic Editor: Andrzej Katunin

Copyright © 2022 Chuan Zhao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The aim of the current study was to investigate the effects of strain rate and metallographic structure on the fracture mode and fracture pattern of a typical shell steel material under impact loading. A ballistic gun was used to launch a spherical tungsten alloy projectile to impact target 50SiMnVB and 60Si2Mn steel plates. The morphological characteristics of the cracks on different target plates were observed under a metallurgical microscope, and the effects of the strain rate and metallographic structure on the fracture mode and fracture pattern were analyzed. The results showed that when the strain rate was relatively low, the material mainly produced ductile fracture and brittle trans-granular fracture under impact loading; when the strain rate was relatively high, intergranular fracture and cleavage fracture were the main modes of fracture under impact loading. In addition, at higher strain rates, the metallurgical form mainly influenced the pattern of fracture of the material, with tempered troostite being more likely to produce a mixture of shear and tensile fractures than tempered sorbite. The results obtained provide an experimental basis for the mechanism of microscopic fracture of shell steel materials and, to a certain extent, reveal the correlations between fragmentation and the strain rate and microstructure of the material.

1. Introduction

To adapt to the harsh firing environment and in consideration of the cost, the ammunitions of most barreled weapons, such as grenades and mortar shells, are made of monolithic structures, which produce natural fragments of varying shapes and masses upon explosion. The fragmentation results (i.e., the distribution of the number of fragments with their mass) of the shell under the action of a blast load conform to certain statistical patterns [1]. Through the tireless efforts of many researchers [2–4], the mass distribution behaviors of natural fragments were summarized into the generally recognized and accepted Weibull distribution model (Mott distribution is its special case). The Weibull distribution is a two-parameter distribution with two control parameters: the scale parameter μ and the shape parameter β . Mott et al. [5] and Grady [6] interpreted μ as the characteristic mass of the fragments, which reflected the magnitude of the average mass of the fragments, and derived expressions for calculating it.

Mock and Holt [7] analyzed the effects of different heat treatment processes and mechanical properties of materials on μ . Chhabildas et al. [8] analyzed the effect of the strain rate and fracture toughness on μ . Zhang et al. [9] proposed that the shape parameter β was related to the homogeneity of the fragments and investigated the influence of the shell shape on μ . Zhao et al. [10] tested the fragmentation of materials of eight states and found that Mott and Grady's theory has a limitation in that μ is not always positively correlated with the fragmentation resistance factor. They also related μ to the average grain diameter and found that the larger the grain size was, the larger the average mass of the fragments became. The above studies showed that it is still an unsolved problem to analyze in detail the factors influencing the values of the control parameters of the distribution model, to specify their physical meanings, and to establish a calculation method that can predict their values more accurately. To solve the above problems, an in-depth study of the fracture mechanism of shells is required.

The problem of fragmentation of a shell under blast loading is a typical impact dynamics problem, and the major difference with static or quasi-static loading is that the material will exhibit completely different response behaviors at high strain rates, such as strain rate strengthening and tough–brittle transitions [11]. Osovski et al. [12] studied the effect of the strain rate on the material fracture and found that as the strain rate increased, the fracture resistance coefficient and the plastic energy dissipation increased. Moses et al. [13] carried out numerical simulations of the expansion ring breakage at different strain rates and found that the material plasticity decreased and the total number of fragments increased with increasing strain rates. Johnson and Cook [14] established a failure criterion that takes into account the strain rate of the material through a series of tensile tests, which is widely used in the numerical calculation of impact dynamics problems. Khan and Liu [15] proposed a strain-rate-dependent failure model based on a stress vector criterion. Fuzuli et al. [16] derived a strain-rate-dependent failure criterion using the energy method, which was in good agreement with experimental results. With the development of fracture physics, the fracture of materials under impact loading has also been linked to the microstructure. A number of experimental studies [17–25] investigated the effects of different microstructures, especially metallographic forms of the structure, on crack extension. Various theoretical studies have been conducted. Zerilli and Armstrong [26] developed an intrinsic structural model that takes into account the influence of the material microstructure. Bourne et al. [27–29] and others have carried out a number of studies to analyze the influence of the material crystal structure on the fracture behavior and proposed a method to calculate the fracture strength based on the number of microscopic defects, such as dislocations and holes in the material. They concluded that there was a correlation between the number of microscopic defects and the grain size of the material. Ren et al. [30] developed an intrinsic model for calculating explosive fragmentation considering the crystallographic characteristics of the material and achieved good results.

The above results focused on one of the two important influencing factors at a time, strain rate or microstructure, and there is a lack of research on the fracture mechanism of materials where both factors were considered. To determine the mechanism of microscopic fracture of materials under impact loading, provide a detailed analysis of the factors influencing the fragmentation of the shell, and analyze the influence of each factor on the mass distribution of the fragments in detail, it is necessary to systematically analyze the influence of the strain rate and material microstructure on the fracture mode and fracture pattern.

Two types of steel, 50SiMnVB and 60Si2Mn steel, are typical silicon-manganese series of shell steel materials with high strength, plasticity, and toughness. Compared with ordinary high strength alloy steel, they will break into more fragments under explosion, so they are widely used in the manufacture projectiles of barreled weapons, such as grenades and mortar shells [10]. These two typical shell steel materials were selected for this study, and two different heat

treatment processes were used to change the metallurgical structures of the materials to obtain four material states. Materials in each state were processed into three target plates, and a total of 12 target plates were used. A ballistic gun was used to fire spherical tungsten alloy projectiles to impact load of the target plate, and the test was divided into three groups according to the different projectile velocities. The varying projectile velocities were used to create varying strain rates on the target plates, with lower projectile velocities creating lower strain rates. The loaded target plate was dissected, and the fracture pattern and the fracture mode of the cracks near the crater were analyzed and generalized under a metallurgical microscope. Through a comprehensive data analysis, the correlations between the crack fracture patterns and fracture modes with the strain rate and metallographic forms were determined to provide an experimental basis for the study of the mechanism of microscopic fracture of typical shell steel materials under impact loading and to attempt to reveal the correlation between fragmentation and the strain rate and material microstructure.

2. Materials and Methods

2.1. Material Preparation. In order to keep with the same state of the shell steel used to manufacture projectiles, the two kinds of steels we used were all obtained by hot rolling and annealing after industrial smelting. A quenching + tempering process was used as the final heat treatment process, and the metallographic form of the material was controlled by changing the tempering temperature. Both tempered troostite and tempered sorbite have good overall mechanical properties, and this study focuses on the effects of these two metallurgical structures on the fracture modes and the fracture patterns of the materials. Two heat treatment processes were designed for each type of shell steel, resulting in a total of four different states of the material, as shown in Table 1. The metallographic structures of the materials numbered I and III obtained by high-temperature tempering corresponded to tempered sorbite, and the metallographic structures of the materials numbered II and IV obtained by medium-temperature tempering corresponded to tempered troostite. The quasi-static mechanical properties of the materials in four states were tested by uniaxial tensile test. The sample in the quasi-static tensile test had a strain rate of 10^{-3} s^{-1} . Since the quasi-static mechanical properties of steel are relatively stable, the test was performed only twice in the same state. After calculation, the standard deviation of strength was less than 9.2, and the standard deviation of plasticity was less than 0.7. The arithmetic mean of the test results was taken as the final quasi-static mechanics performance parameter in each state, and the test results are shown in Table 2, where σ_s (MPa) is yield strength, σ_b (MPa) is tensile strength, δ is elongation, and ψ is the reduction of cross section. The strength of 50SiMnVB was similar to that of 60Si2Mn, and the plasticity of 60Si2Mn was slightly better than that of 50SiMnVB. When the material type was the same, the metallographic structure of tempered troostite had higher strength and lower plasticity than tempered sorbite.

TABLE 1: Four material states.

Material	Heat treatment process		Metallographic structure	Number
	Quenching	Tempering		
50SiMnVB	Keep at 880°C for 60 min, oil cooled	Holding temperature at 550°C for 90 min, water cooling	Tempered sorbite	I
		Holding temperature at 450°C for 90 min, water cooling	Tempered troostite	II
		Holding temperature at 550°C for 90 min, water cooling	Tempered sorbite	III
60Si2Mn		Holding temperature at 450°C for 90 min, water cooling	Tempered troostite	IV

TABLE 2: Quasi-static mechanical properties of materials in four states.

Number	Material	Metallographic structure	σ_s (MPa)	σ_b (MPa)	δ (%)	ψ (%)
I	50SiMnVB	Tempered sorbite	1078.5	1181.5	11.5	23.0
II		Tempered troostite	1382.5	1478.5	8.5	19.5
III	60Si2Mn	Tempered sorbite	1023.5	1207.5	12.5	24.0
IV		Tempered troostite	1317.5	1502.5	10.0	21.5

Common test methods used in the study of the impact dynamics include expansion ring, split Hopkinson pressure bar (SHPB), ballistic gun, and flat plate impact tests. To achieve the objectives of this study, to investigate the effect of the strain rate on the fracture mode and fracture pattern of the material, and to further analyze the fragmentation of the shell, a test method that can vary the strain rate of the material over a wide range while the strain rate is close to the strain rate of the shell under blast loading (typically 10^4 – 10^5 s⁻¹) is required. The ballistic gun test can vary the strain rate in the loaded area of the target plate by changing the velocity of the projectile over a wide range, usually in the range of 10^2 – 10^4 s⁻¹ [11]. Thus, a ballistic gun was selected for the impact loading tests in this study. The tests were divided into three groups according to the projectile velocity, with the Group-1 test projectiles having a target velocity of 1000 m/s, Group-2 test projectiles having a target velocity of 700 m/s, and Group-3 test projectiles having a target velocity of 400 m/s. For the Group-1 tests, the strain rate in the loaded area of the target plate was expected to be of the order of 10^4 s⁻¹. For both Group-2 and Group-3 tests, the strain rates in the loaded areas of the target plates were expected to be of the order of 10^3 s⁻¹, with the strain rate of the target plate in Group 3 being lower than that of the target plate in Group 2.

As the test was divided into three groups, three target plates were machined for each state, and a total of 12 target plates were prepared. A ballistic gun was used to launch a tungsten projectile to impact load of the target plate. The tungsten projectile was spherical in shape, with a diameter of 10 mm and a mass of 9.2 g. To prevent the projectile from penetrating the target plate during loading, the target plate should have a certain thickness; the target plate size was $140 \times 140 \times 35$ mm. The dimensions of the target plate used for the test are shown in Figure 1(a). The spherical tungsten alloy projectile and the projectile sabot are shown in Figure 1(b). The ballistic gun used in the test was 12.7 mm in

diameter, but the diameter of spherical projectile was 10 mm. To ensure that the projectile matches the caliber of the ballistic gun, it is necessary to prepare a nylon sabot for the projectile, as shown in Figure 1(b). At the same time, the sabot can also seal the gunpowder gas and ensure the velocity of the projectile during firing. The surface of the sabot was pregrooved so that after discharge the sabot was torn in half by air resistance and then separated from the projectile, so as to prevent the sabot from interfering with the normal work of the electronic velocimeter.

2.2. Ballistic Gun Test. A ballistic gun with a diameter of 12.7 mm from the East Garden Test Base of Beijing Institute of Technology was used. The speed of the projectile was controlled by changing the mass of the charge, and the greater the mass of the charge was, the greater the velocity of the projectile became, usually in the range of 300–1000 m/s. The electronic velocimeter was used to determine the velocity of the projectile during the test. The ballistic gun test setup is shown in Figure 2, and the field layout of the ballistic gun test is shown in Figure 3. As shown in Figure 2, the ballistic gun was aimed at the telocentric target net and the geometric center of the target plate for shooting. When the projectile crossed the first layer of the telocentric target net, the electronic timer began timing. When the projectile crossed the second layer of the telocentric target net, timing ended. The distance between the two target nets was divided by the duration recorded by the timer to obtain the velocity v_0 (m/s) before the projectile hit the target.

Based on the different speeds of the projectile, the test was divided into three groups. Each group was shot once at the target plate made of materials of four states. The same mass of gunpowder was loaded for each shot in the same group of tests, and the mass of gunpowder was loaded differently in the different groups. In the test, the projectile velocity v_0 was measured for each target plate, and the results

FIGURE 1: Target plate, projectile, and sabot. (a) Target plate. (b) Spherical tungsten alloy projectile and sabot.

FIGURE 2: Schematic diagram of the ballistic gun test setup.

FIGURE 3: Layout of the ballistic gun test. (a) Ballistic gun. (b) Speed measurement circuit and target board.

are shown in Table 3. The average velocity of the first group of test projectiles was 994.22 m/s, and the relative deviation of the minimum velocity from the maximum velocity was 3.32%. The average velocity of the second group of test projectiles was 769.67 m/s, and the relative deviation between the minimum and maximum velocity was 3.37%. The average velocity of the third group of test projectiles was 410.31 m/s, and the relative deviation between the minimum and maximum velocity was 5.78%. The consistency of the projectile velocities corresponding to the four target plates of each group of tests was high, and the average velocities of the projectiles in the three groups of tests were more consistent

with the target velocity. The strain rates of the loaded areas of the target plates of the three groups of tests gradually decreased.

2.3. Target Plate Sectioning, Grain Etching, and Crack Observation. The 12 target plates subjected to projectile impact loading were sectioned along the crater axis, and the sectioning method and observation area are shown in Figure 4. According to Figure 4, the 12 target plates near the craters were made into samples to be observed. The craters in the observation areas of the 12 samples and the shapes of the

TABLE 3: Projectile velocities corresponding to different target plates.

Group number	v_0 ($m \cdot s^{-1}$)				Average velocity of projectiles ($m \cdot s^{-1}$)	Relative deviation of minimum and maximum velocities (%)
	I	II	III	IV		
A	973.42	1000	996.6	1006.87	994.22	3.32
B	785.52	763.02	759.07	771.05	769.67	3.37
C	393.82	412.68	417.97	416.79	410.31	5.78

Note: in Table 2, “A” means the first group of tests, and the velocity of the projectile was 1000 m/s. “B” is the second group of tests, with a target velocity of 700 m/s. “C” is the third group, with a target velocity of 400 m/s.

FIGURE 4: Schematic diagram of the sectioning method of the target plate and the observation area.

cracks near the craters are shown in Figures 5(a)–5(i). The cracks discernible to the naked eye near the crater of each sample which were the main observation objects were marked with red circles, as also shown in Figures 5(a)–5(i). Near the crater entrance of the 12 target plates, the material exhibited a certain degree of accumulation, which was due to the plastic flow of the target plate material along the crater axis under the projectile impact loading. Part of the target plate material was squeezed toward the crater entrance to produce this phenomenon, indicating that the materials of the four states all embodied a certain degree of plasticity under the projectile loading. In the first group of tests, the crater bottoms of target plates A-I and A-III were similar, with smooth arc shapes. The crater bottoms of target plates A-II and A-IV were similar, with conical shapes. In the remaining two groups of tests, the target plate crater bottoms were not significantly different, with smooth arc shapes. The reasons for this phenomenon will be further discussed in Section 3.2.

The observed areas of the 12 target plates were further investigated. To study the crack morphology and the relationship between crack extension and material microstructure, the grain boundary etching method [31] was used to treat the 12 specimens. The specific corrosion etching method was as follows:

- (1) A beaker was filled with 100 ml of water. Next, 5–7 g of picric acid and 0.5–1.5 g of active agent (Hai-O brand shampoo cream) were added. The mixture was heated in a resistance furnace to boiling (100°C) and kept warm for 3–5 min while continuously stirring to keep the solution well mixed.
- (2) The resistance furnace was turned off, and 0.1–0.2 ml (1–2 drops) of hydrochloric acid was added to the beaker to obtain a chemical etching solution for backup.

- (3) The resulting chemical etching solution was cooled to $40\text{--}50^{\circ}\text{C}$ (at this time, a bitter acid precipitated from the solution), and the etching solution was diluted 10 times. The solution was heated again, and the temperature was raised to $60\text{--}70^{\circ}\text{C}$. The 12 specimens were immersed in the corrosion solution, the solution was stirred for 20–22 s, and the specimens were removed. The specimens were then cleaned and dried.

A metallurgical microscope (Model: Axio Observer Z1) was used to observe the cracks with red circles of the 12 samples. Micrographs of all cracks with red circles were taken in turn, as shown in Figures 6(a)–6(w). Taking sample “A-I” for example, there were three cracks marked with red circles. Thus, three micrographs were taken as shown in Figures 6(a)–6(c). As shown in Figures 6(a)–6(w), the grain boundary corrosion method could be used to show the grains and grain boundaries of the four states of the material more clearly.

Note: the meaning of the symbols in Figure 6 is as follows. Taking crack “A-I-1” shown in Figure 6(a) as an example, “A” means the first group of tests, “I” means the material of the target plate, which corresponds to the material numbered I in Table 1, and the number “1” means the crack in the red circle marked as “1” on the target plate of A-I in Figure 5(a).

3. Analysis and Discussion

3.1. Effect of Strain Rate on the Fracture Mode. The fracture of materials under impact loading can be divided into ductile fracture and brittle fracture [11], and brittle fracture can be further divided into intergranular fracture, trans-granular fracture, and cleavage fracture based on the relationship between the crack and the grain boundary. Figure 7 shows crack

FIGURE 5: Observation areas of the 12 target plates. (a) A-I. (b) A-II. (c) A-III. (d) A-IV. (e) B-I. (f) B-II. (g) B-III. (h) B-IV. (i) C-I. (j) C-II. (k) C-III. (l) C-IV.

C-II-1 on target plate C-II. The position shown by the red arrow is the end of the crack, and the end of the crack is blunt. The blue box shows the expansion path of the crack. The crack passes through some voids in the process of propagation, and these voids were generated by the plastic deformation of the material under the action of an impact load. Crack C-II-1 was determined to be a typical ductile fracture.

Figure 8 shows crack B-III-2 on target plate B-III. The red arrow shows the end of the crack, and the tip of the crack was sharp. The blue box shows the crack propagation path, and the crack propagated along the grain boundary. Thus, crack B-III-2 was a brittle fracture, and it was a typical intergranular fracture. Figure 9 shows crack A-III-1 on target plate A-III. The crack consisted of a group of cracks with a certain regularity in the direction of expansion, and the ends of the cracks were all relatively sharp. The crack in the red box in the figure was a trans-granular fracture, and the crack in the blue box was an intergranular fracture. Thus, crack A-III-1 was a typical brittle cleavage fracture. The crack expanded along the decomposed surface of the crystal, and the crack direction showed a certain regularity. Figure 10 shows crack B-I-1 on target plate B-I. The red arrow in the figure shows the end of the crack, which was relatively sharp. The expansion path of the crack was approximately a straight line, and the expansion of the surface crack was not affected by the microstructure of the material. Thus, crack B-I-1 was a trans-granular fracture unrelated to the grains.

The fracture modes of all the cracks shown in Figures 6(a)–6(w) were discriminated, and the results are shown in Table 4. Ductile fracture only appeared in target plates C-I, C-II, and C-IV, and these three target plates were all from the third group of tests. The strain rate in the loaded area of the target plate was the smallest. For the other two groups of target plates with higher strain rates, the cracks in the observed area were brittle fracture. Under the impact load, the fracture modes of the materials in the four states changed from ductile fracture to brittle fracture as the strain rate increased. According to Meyers [11], for ductile materials, the fracture toughness of a material increases as the strain rate increases. For brittle materials, the fracture toughness of a material decreases as the strain rate increases. This indicates that the typical shell steel material studied was a brittle material under impact loading.

Among the four fracture modes produced by the 12 target plates under impact loading, ductile fracture and trans-granular fracture were independent of the grain boundaries of the material, while intergranular fracture and cleavage fracture were influenced by the grain boundaries. As shown in Table 3, the four target plates made of different material states in the Group-1 tests all showed grain-related intergranular fracture or cleavage fracture in the observation area. Specifically, all cracks in target plates A-I and A-II were grain-related, two of the three cracks in the observation area of target plate A-III were grain-related, and one of the two

FIGURE 6: Crack morphology in the observation area of the 12 target plates. (a) A-I-1, 200x. (b) A-I-2, 500x. (c) A-I-3, 200x. (d) A-II-1, 500x. (e) A-II-2, 500x. (f) A-III-1, 200x. (g) A-III-2, 200x. (h) A-III-3, 200x. (i) A-IV-1, 200x. (j) A-IV-2, 500x. (k) B-I-1, 200x. (l) B-I-2, 200x. (m) B-II-1, 200x. (n) B-II-2, 200x. (o) B-III-1, 200x. (p) B-III-2, 200x. (q) B-IV-1, 200x. (r) B-IV-2, 200x. (s) C-I-1, 200x. (t) C-I-2, 200x. (u) C-II-1, 200x. (v) C-III-1, 500x. (w) C-IV-1, 200x.

FIGURE 7: Crack C-II-1, typical ductile fracture, 200x. The red arrow indicates the location of the end of the crack, which was blunt. The blue box shows the crack passing through the void created by plastic deformation of the material during expansion.

FIGURE 8: Crack B-III-2, typical intergranular fracture, 200x. The red arrow indicates the location of the end of the crack, which was sharp. The blue box shows the crack expansion path, where the crack propagated along the grain boundary.

cracks in the observation area of target plate A-IV was grain-related. Only one grain-related crack appeared in target plate B-III in the Group-2 tests, and no grain-related cracks appeared in the Group-3 tests. In the four states, as the strain rate increased, the material gradually produced grain-related cracks under the impact load, and the number of grain-related cracks relative to the total number of cracks also showed an increasing trend.

3.2. Influence of the Metallographic Structure and Strain Rate on the Fracture Pattern. As shown in Figures 5(a)–5(d), the crater bottoms of target plates A-I and A-III in the Group-1 tests were smoothly curved, while the crater bottoms of target plates A-II and A-IV were more sharply tapered. In addition, as shown in Figures 5(e)–5(l), the crater bottom shapes of each target plate in the Group-2 and Group-3 tests were smoothly curved. The damage shape of the material was related to the fracture pattern of the target plate material. The material fracture was divided into tensile fracture and shear fracture, where the tensile fracture was perpendicular to the maximum positive stress direction, and the shear fracture was parallel to the maximum tangential stress direction and at a 45° angle to the direction of the maximum positive stress. The response of the target plate under the

FIGURE 9: Crack A-III-1, typical cleavage fracture, 200x. The crack in the red box is transgranular fracture, and the crack in the blue box is intergranular fracture. The crack extended along the decomposed surface.

FIGURE 10: Crack B-I-1, typical trans-granular fracture, 200x. The red arrow indicates the position of the end of the crack, which was sharp. The blue box shows the expansion path of the crack, which was approximately straight.

action of the projectile was simplified to a plane strain problem [32]. When the projectile acted on the target plate instantaneously, the maximum shear stress and the maximum positive stress of the target plate microelement on the contact surface reached the maximum value at the same time. Combined with Figures 5(a)–5(l), the angle between the initial crack expansion direction and the maximum positive stress direction (projectile velocity direction) in the observation areas of the 12 target plates connected with the crater was approximately 45° , so the initial crack was shear fracture.

Crack fracture patterns in the observed areas of the four target plates of the Group-1 test were analyzed. In Figures 6(a)–6(w), cracks A-II-2 (shown in Figure 6(e)), A-III-1 (shown in Figure 6(f)), and A-IV-1 (shown in Figure 6(i)) were produced at (or near) the end of the initial crack with a different direction from the initial crack extension. Figure 11 shows crack A-II-2 on target plate A-II. The crack shown by the blue arrow is the initial shear fracture, and the crack expansion direction shown by the red arrow had a more significant difference from the initial crack. The angle between the two crack expansion directions was about 46° , and thus, the crack shown by the red arrow

TABLE 4: Fracture mode in the observation areas of 12 target plates.

Target plate	Crack 1	Crack 2	Crack 3	Target plate	Crack 1	Crack 2	Crack 3
A-I	Intergranular fracture	Intergranular fracture	Intergranular fracture	A-III	Cleavage fracture	Cleavage fracture	Trans-granular fracture
B-I	Trans-granular fracture	Trans-granular fracture		B-III	Trans-granular fracture	Intergranular fracture	
C-I	Ductile fracture	Trans-granular fracture		C-III	Trans-granular fracture		
A-II	Intergranular fracture	Intergranular fracture		A-IV	Trans-granular fracture	Cleavage fracture	
B-II	Trans-granular fracture	Trans-granular fracture		B-IV	Trans-granular fracture	Trans-granular fracture	
C-II	Ductile fracture			C-IV	Ductile fracture

FIGURE 11: Crack A-II-2, shear-tension hybrid fracture, 500x. The crack shown by the blue arrow is the initial shear fracture. The crack shown by the red arrow and the crack shown by the green arrow are both tensile fracture.

was determined to be tensile fracture. The crack shown by the green arrow was not connected with the initial crack, and the angle between the expansion direction of the crack shown by the green arrow and the tensile fracture shown by the red arrow was about 108° . Because the velocity direction of the projectile was not strictly parallel to the normal direction of the target plate and the systematic errors were generated during the sectioning of the target plate, photographing of the plate, and measurement, the two cracks were considered to be perpendicular to each other and were at angles of 45° with the initial shear fracture shown by the blue arrow and the tensile fracture shown by the red arrow. The initial shear fracture shown by the blue arrow was at an angle of 45° , so the crack shown by the green arrow was tensile fracture.

Figure 12 shows crack A-III-1 on target plate A-III. The crack shown by the blue arrow is the initial shear fracture; the angle between the expansion direction of the crack shown by the red arrow and the crack shown by the blue arrow was about 108° . By neglecting the error, these two cracks can be considered to be perpendicular to each other, so the crack shown by the red arrow is a shear fracture. Figure 13 shows crack A-IV-1 on target plate A-IV. The crack shown by the blue arrow is the initial shear fracture, and the angle between the crack expansion direction shown by the red arrow and the initial crack was about 40° . By

neglecting the error, the crack shown by the blue arrow can be considered to be a tensile fracture with the initial shear crack at 45° .

The metallographic structures of target plates A-I and A-III were consistent with the structure of tempered sorbite, and the metallographic structures of target plates A-II and A-IV were consistent with the structure of tempered troostite. In Group 1, a mixture of shear and tensile fracture occurred in the observed areas of target plates A-II and A-IV. Target plates A-I and A-III in the observation area only exhibited shear fracture. In the vicinity of the initial shear crack, there may be other shear cracks with the extension direction perpendicular to the initial crack. In Groups 2 and 3, as shown in Figures 5(e)–5(l), the shapes of the bottoms of the craters of all eight target plates were smooth and curved. As shown in Figures 6(k)–6(w), the fracture pattern of the cracks in the observation area of all eight target plates was shear fracture. In summary, the metallurgical structure form and strain rate of the target plate were important factors affecting the fracture pattern of the material under the action of an impact load. At lower strain rates, the material only underwent shear fracture. At higher strain rates, the material could have a mixture of both shear and tensile fracture. When the strain rate was high, for typical shell steel materials, the metallographic form of tempered troostite was more likely to produce a mixed fracture under both shear and tension than tempered sorbite. The reason for this phenomenon may be related to the mechanical properties. It can be seen from Table 2 that when the material type was the same, the tempered troostite had higher strength and lower plasticity than the tempered sorbite. However, further experiments are needed to verify this correlation, especially to test the dynamic mechanical properties of these two metallurgical structures.

3.3. Relationship between Characteristic Mass of Fragments and the Fracture Mode and Pattern. In a previous study [10], the relationship between the fragmentation and material microstructure of four typical shell steel materials (D60, 58SiMn, 50SiMnVB, and 35CrMnSiA) in two heat treatment states (high-temperature tempering and medium-temperature tempering) was investigated, and the following

FIGURE 12: Crack A-III-1, shear fracture, 200x. Both the crack shown by the blue arrow and the crack shown by the red arrow are shear fractures.

FIGURE 13: Crack A-IV-1, shear-tension hybrid fracture, 200x. The blue arrow shows the crack of the initial shear fracture. The red arrow shows the crack of tensile fracture.

conclusions were drawn from the preliminary analysis of the results of the shell fragmentation tests [10]:

- (1) There was a stronger correlation between the characteristic masses of the fragments (which were positively correlated with the average mass) and the average grain size of the material.
- (2) When the average grain size of the material did not vary, there was a correlation between the metallographic structural form and the characteristic mass of the fragments. The characteristic mass of the fragments of tempered troostite was greater than that of tempered sorbite.

The effect of the strain rate and metallurgical structure on the fracture mode and the fracture pattern of the material under impact loading could help to further understand the reasons for the phenomena described above. The strain rates of the target plate for the current three groups of ballistic gun tests ranged from 10^3 to 10^4 s^{-1} , with the strain rate for the first group of tests being about 10^4 s^{-1} and the strain rates for the second and third groups of tests being about 10^3 s^{-1} . According to the experimental results, the majority of cracks in the observed area of the target plate in the Group-1 tests with a strain rate of 10^4 s^{-1} were intergranular or cleavage fractures related to the grain boundaries of the material, while there were almost no grain-related cracks in the

observed area of the target plate in the Group-2 and Group-3 tests with lower strain rates. This indicates that as the strain rate of the target plate increased, the fracture mode of the material under impact loading changed from ductile fracture or brittle trans-granular fracture to intergranular fracture or cleavage fracture. The strain rate range of shell materials under explosive loading is usually 10^4 to 10^5 s^{-1} , so it can be presumed that when the shell steel material was at a higher strain rate, the material fractured mainly by intergranular or cleavage fracture, both of which are closely related to the grain properties. Therefore, as the final result of the material fracture damage, the average mass of the fragments (or characteristic mass) should reflect the effect of the grain size.

According to the results of the ballistic gun test, the metallographic form of the material at higher strain rates affected the final fracture results mainly by influencing the fracture pattern. At lower strain rates, tempered troostite and tempered sorbite only underwent shear fracture. With increasing strain rates, tempered troostite tended to produce shear-tension hybrid fractures compared to tempered sorbite. It is inferred that, under higher strain rates of the blast loading, a greater number (or a higher percentage) of hybrid fractures are produced for typical shell steel materials with a metallographic structure in the form of tempered troostite compared to temper sorbite. When the material composition and grain size were the same, shear fractures produced smaller fragments, while hybrid fractures produced larger fragments. Thus, the fragmentation characteristic mass of tempered troostite was greater than that of tempered sorbite. However, the correlation between the average mass of the fragments and the fracture pattern was concluded here based on the common phenomenon that appeared in ballistic gun and fragmentation tests. Thus, it is necessary to conduct fragmentation tests and adopt a morphological method to verify this correlation.

4. Conclusions

In this study, two typical shell steel materials were selected, and two different heat treatments were carried out to obtain four states of the material. For each state, three target plates were prepared. The ballistic gun was used to launch a spherical tungsten alloy projectile to impact load of a target plate. The test was divided into three groups based on the projectile velocity, and a lower projectile velocity corresponded to a lower strain rate of the target plate. The loaded target plate was dissected, and the morphologies of the cracks near the crater were observed under a metallurgical microscope. The correlations between the crack fracture mode and fracture pattern and the strain rate and metallurgical structure were analyzed. The study showed the following:

- (1) For the four material states, as the strain rate increased, the material gradually developed grain-related fracture modes, i.e., intergranular fracture and cleavage fracture, under impact loading, and the proportion of grain-related cracks to the total number of cracks also gradually increased.

- (2) Under impact loading, the metallurgical structure and strain rate of the target plate are important factors affecting the fracture pattern of the material. At lower strain rates, the material will only undergo shear fracture. At higher strain rates, the material may have a mixture of both shear and tensile fracture. When the strain rate is high, materials with tempered troostite metallographic structures tend to produce mixed fracture in shear and tension at the same time compared to tempered sorbite.
- (3) Under explosive loading, a stronger correlation was observed between the characteristic mass of the fragments and the average grain diameter of typical shell steel materials, which may have been due to a greater tendency to produce intergranular fracture or cleavage fracture at high strain rates. When the material composition and grain size were constant, the tempered troostite produced a greater average mass of fragments than the tempered sorbite, which may have been due to the fact that, at high strain rates, tempered troostite tended to produce a mixture of shear and tensile fractures simultaneously.

Data Availability

All data, models, and codes generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Basic Research Program of China (Grant no. 613305). China State Key Laboratory of Explosion Science and Technology and Shenyang Ligong University are acknowledged.

References

- [1] D. Grady, *Fragmentation of Rings and Shells*, Springer, Berlin Heidelberg, 2006.
- [2] C. C. Lienau, "Random fracture of a brittle solid," *Journal of the Franklin Institute*, vol. 221, no. 5, pp. 673–686, 1936.
- [3] N. F. Mott and E. H. Linfoot, *A Theory of Fragmentation*, AC3348, Ministry of Supply, British, UK, 1943.
- [4] D. E. Grady and M. E. Kipp, "Geometric statistics and dynamic fragmentation," *Journal of Applied Physics*, vol. 58, no. 3, pp. 1210–1222, 1985.
- [5] N. F. Mott, "Fragmentation of shell cases," *Proceedings of the Royal Society of London - Series A: Mathematical and Physical Sciences*, vol. 189, no. 1018, pp. 300–308, 1947.
- [6] D. E. Grady and E. Dennis, "Particle size statistics in dynamic fragmentation," *Journal of Applied Physics*, vol. 68, no. 12, pp. 6099–6105, 1990.
- [7] W. Mock and W. H. Holt, "Fragmentation behavior of Armco iron and HF-1 steel explosive-filled cylinders," *Journal of Applied Physics*, vol. 54, no. 5, pp. 2344–2351, 1983.
- [8] L. C. Chhabildas, T. F. Thornhill, W. D. Reinhart et al., "Fracture resistant properties of AerMet steels," *International Journal of Impact Engineering*, vol. 26, no. 1–10, pp. 77–91, 2001.
- [9] Z. Zhang, F. Huang, Y. Cao, and C. Yan, "A fragments mass distribution scaling relations for fragmenting shells with variable thickness subjected to internal explosive loading," *International Journal of Impact Engineering*, vol. 120, pp. 79–94, 2018.
- [10] C. Zhao, S. Wang, C. Guo, D. Liu, and F. Ma, "Experimental study on fragmentation of explosive loaded steel projectile," *International Journal of Impact Engineering*, vol. 144, Article ID 103610, 2020.
- [11] M. A. Meyers, *Dynamic Behavior of Materials*, National Defense Industry Press, Beijing, China, 2006.
- [12] S. Osovski, A. Srivastava, L. Ponson et al., "The effect of loading rate on ductile fracture toughness and fracture surface roughness," *Journal of the Mechanics and Physics of Solids*, vol. 76, pp. 20–46, 2015.
- [13] J. F. Moxnes, A. K. Prytz, Ø. Frøyland, S. Skriudalen, S. Børve, and G. Ødegårdstuen, "Strain Rate Dependency and Fragmentation Pattern of Expanding Warheads," *Defence Technology*, vol. 11, 2015.
- [14] G. R. Johnson and W. H. Cook, "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures," *Engineering Fracture Mechanics*, vol. 21, no. 1, pp. 31–48, 1985.
- [15] A. S. Khan and H. Liu, "Strain rate and temperature dependent fracture criteria for isotropic and anisotropic metals," *International Journal of Plasticity*, vol. 37, pp. 1–15, 2012.
- [16] F. A. Akay and E. Oterkus, "A criterion for dynamic ductile fracture initiation of tensile mode," *Continuum Mechanics and Thermodynamics*, no. 4, 2021.
- [17] J. C. Beetle, "SEM/1971(Part 1)," in *Proceedings of the Fourth Annual SEM Symposium*, pp. 137–144, Research Institute, Chicago, Illinois, April, 1971.
- [18] B. Crossland, "Mechanical properties at high rates of strain," *Physics Bulletin*, vol. 27, no. 1, p. 30, 1976.
- [19] J. Pearson and J. S. Rinehart, "Deformation and fracturing of thick-walled steel cylinders under explosive attack," *Journal of Applied Physics*, vol. 23, no. 4, pp. 434–441, 1952.
- [20] D. M. Goto, R. Becker, T. J. Orzechowski, H. K. Springer, A. J. Sunwoo, and C. K. Syn, "Investigation of the fracture and fragmentation of explosively driven rings and cylinders," *International Journal of Impact Engineering*, vol. 35, no. 12, pp. 1547–1556, 2008.
- [21] S. Sui, M. Wang, and X. Ma, "An experimental research on material fracture mechanism in explosive loading," *Transactions of Beijing Institute of Technology*, vol. 20, no. 2, pp. 197–200, 2000, in Chinese.
- [22] B. Hu, Q. Dong, C. Han, D. Wang, and H. Hu, "Studies of expansion and fracture of explosive-filled steel cylinders," *Explosion and Shock Waves*, vol. 13, no. 1, pp. 49–54, 1993, in Chinese.
- [23] J. Yan, E. Min, and S. Zhang, "Analysis of large diameter grenade steel fragments," *Ordnance Material Science and Engineering*, vol. 6, no. 1, pp. 51–59, 1983, in Chinese.
- [24] C. Wu, Y.-G. Ni, Y.-X. Zhang, and D.-M. Ai, "Metallographic analysis of semi-preformed fragment warhead steel shell by different heat treatment," *Transactions of Beijing Institute of Technology*, vol. 28, no. 5, pp. 381–384, 2008, in Chinese.
- [25] X. Kong, W. Wu, Z. Du, and J. Li, "Research on fragments characteristic of cylindrical warhead when detonated at different points," *Harbin Gongcheng Daxue Xuebao/Journal of Harbin Engineering University*, vol. 34, no. 7, pp. 855–861, 2013.

- [26] F. J. Zerilli and R. W. Armstrong, "Dislocation-mechanics-based constitutive relations for material dynamics calculations," *Journal of Applied Physics*, vol. 61, no. 5, pp. 1816–1825, 1987.
- [27] N. K. Bourne, "On the failure and dynamic performance of materials," *Experimental Mechanics*, vol. 52, no. 2, pp. 153–159, 2012.
- [28] N. Bonora, B. Neil, R. Andrew, I. Gianluca, and T. Gabriel, "Investigation on grain size effect in high strain rate ductility of 1100 pure aluminum," in *Proceedings of the 19th Biennial Conference of the APS Topical Group on Shock Compression of Condensed Matter*, vol. 60, no. 8, Tampa, FL, USA, June 2015, <http://meetings.aps.org/link/BAPS.2015.SHOCK.T4.5>.
- [29] S. Fensin, G. Gray, N. Bourne, and R. Hixson, "Microstructure based failure criterion for ductile materials," *EPJ Web of Conferences*, vol. 183, Article ID 03005, 2018.
- [30] B. Ren and S. Li, "A three-dimensional atomistic-based process zone model simulation of fragmentation in polycrystalline solids," *International Journal for Numerical Methods in Engineering*, vol. 93, no. 9, pp. 989–1014, 2013.
- [31] L. I. U. Tian-you and J.-li Tian, "Problems about examining austenite grain size with oxidizing method," *Hot Working Technology*, vol. 17, no. 2, pp. 40–43, 2000, in Chinese.
- [32] J. F. Throop and R. R. Fuczak, "Strain behavior of pressurized cracked thick-walled cylinders," *Experimental Mechanics*, vol. 22, no. 8, pp. 277–286, 1982.