Research on Dynamic Constitutive Model and Fracture Characteristics of Two High Strength Steels

Xiangyu Li*, Fugang Li, Minzu Liang, Kefan Zhang and Zhandong Tian

College of Liberal Arts and Sciences, National University of Defense Technology, Changsha, China
Email: xiangyulee@nudt.edu.cn.

Abstract. 58SiMn and 50SiMnVB are commonly used shell materials in bombs, and their dynamic constitutive model and fracture properties directly determine the mass distribution of the bomb. Tensile tests were carried out on two high-strength steels, and the parameters of the yield point, tensile strength and plastic failure strain as well as the John-Cook model were determined. The fracture morphologies of the two steels in the quasi-static tension and in the dynamic tension were analyzed. The research results show that the yield strength of 58SiMn steel remains unchanged with increasing strain rate. The yield strength and tensile strength of 50SiMnVB increase as the rate of elongation increases, and the ability to plastically deform decreases, which shows the properties of embrittlement under high speed loading. With the same elongation rate, 50SiMnVB steel has higher strength and toughness. 58SiMn steel is a tensile brittle fracture from a macroscopic point of view and a quasi-split fracture from a microscopic point of view; 50SiMnVB steel is a mixed lap shear fracture under axial tensile load. With increasing loading rate, the tensile fracture tends to pure shear fracture.

Keywords. Dynamic constitutive model; high strength steel; fracture characteristics; experiment.

1. Introduction

58SiMn and 50SiMnVB are commonly used shell materials in bombs, and their dynamic constitutive model and fracture properties directly determine the mass distribution of the bomb. The dynamic fracture process of material under internal explosion loading is a very complex physical process. Taylor [1] first proposed the dynamic breaking stress criterion, and the crack first breaks from the outer surface and then expands radially towards the inner surface. The rupture mode should be tensile rupture. Hoggatt [2] thought that the Taylor stress criterion is only valid at lower strain rates through a large number of experimental studies. Numerous research results indicate that tensile fracture and shear fracture are the main types of failure of shell under internal detonation loading. Due to the morphology of the recovered fragments, tensile fractures, tensile shear fractures and mixed failure can occur the rupture mechanism is complex and many factors such as the performance of the material, the power of the explosive, and the structure of the warhead. The initial tensile fracture caused by the cracks on the outside wall of the shell is the main reason for controlling the breakage. It is therefore necessary to conduct experimental studies on the tensile fracture properties of the shell material.

Scientists have studied the mechanical properties of materials through the formation properties of natural fragments. Stronge [3] studied the mass distribution of fragments of low carbon steel and HF-1 steel under different heat treatment conditions and the results showed that the fragmentation properties are related to the ductility of the material. Zecevic [4] found that the ratio of strength (yield strength / tensile strength) has a greater influence on the total number of fragments and that the total number of...
fragments. Shahraini [5] compared the number of effective fragments of two alloyed steels of DIN 1.7035 and 25CrSiNiMo6 and came to the conclusion that alloyed steel with high toughness produces more effective fragments. Wilson [6] used numerical calculation methods to carry out similar investigations. Some other scholars [7-12] have carried out some work on the dynamic fracture and crushing characteristics of different steel materials under conditions of explosion and impact. However, there is less research for 58SiMn and 50SiMnVB steel. High-strength 58SiMn and 50SiMnVB steel are common materials in high explosive bombs, and their dynamic constitutive model and fracture properties directly determine the mass distribution of the bomb. Because the fracture properties of the two alloy steels under detonation loading were not fully taken into account in the design of the warhead structure, this leads to difficulties in the selection of the bomb shell material. This paper focuses on the main failure modes, quasi-static tensile tests and dynamic tensile tests for 58SiMn and 50SiMnVB steel, and stress-strain curves were obtained. Based on the stress-strain curves, the John-Cook constitutive model is adapted. Combining with scanning electron microscope (SEM) recordings of the fragment, the fracture modes of the two high-strength steels are analyzed.

2. Tensile Test of Two Kinds of High-Strength Steel
The quasi-static tensile specimen of 58SiMn and 50SiMnVB steel is designed according to the national standard GB/T228.1-2010 for the tensile strength of metallic materials. The dynamic tensile specimen, a sheet metal specimen, is designed according to the Hopkinson bar. By reducing the length of the uniform deformation section, the axial stress and strain of the entire specimen are quickly unified.

2.1. Quasi-Static Tensile Test
The quasi-static tensile test was divided into room temperature and high temperature test. The room temperature test was controlled by a microcomputer controlled universal electronic testing machine model WDW-500E and the model of the electronic extensometer was YYU-25. The tensile force of the specimen was measured with a force sensor and the deformation within the measuring length of the specimen with an extensometer. The high temperature test range s from 200°C to 700°C, and the test device was an electronic Zwick universal testing machine with a maximum test force of 100 kN and a laser extensometer to measure the tensile elongation. The strain rate was controlled to be 0.001 s⁻¹. To ensure the consistency of the test data, the tensile test was repeated 3 to 4 times for each specimen.

The application of the engineer stress-strain method can no longer precisely describe the actual stress-strain ratio of the material. Assuming that the material volume does not change, the engineer stress and strain are converted into true stress and true strain. Figure 1 shows the true stress-strain curves of the two high-strength steels at room temperature and high temperatures. It can be seen that as the temperature of the test increases, the yield strength and tensile strength decrease, which shows a significant thermal softening effect.

![Figure 1. Quasi-static true stress-strain curves of two steels at room and high temperatures.](image-url)

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2.2. Dynamic Tensile Test

The tensile dynamic mechanical properties of 58SiMn and 50SiMnVB steel were measured by a Hopkinson bar test. The data processing method of the quasi-static tensile test is the same to get the true stress-strain curves. Ultra-high speed Kirana-01M camera was used to observe the fracture of the specimen during tensile test. Figure 2 is a continuous high speed photograph of the specimen before and after fracture under a single tensile load.

![Figure 2. Breakage of the specimen under a single tensile load.](image)

Figure 3 shows the true stress-strain curves of the two steels in the strain rate range of 800-2700 s^{-1}. The yield strength of 58SiMn steel remains unchanged, which shows the properties of insensitivity to the strain rate. The brittle fracture of 58SiMn steel occurs under dynamic tensile load, and its failure strain is influenced by the internal defects of the material and has a certain randomness. With increasing strain rate, the yield strength and tensile strength of the 50SiMnVB steel increase, which has an increasing strain rate effect, and the hardening index decreases, which is due to the high strain rate and the adiabatic temperature which causes the temperature softening effect.

![Figure 3. The true stress-strain curves of two steels at dynamic tensile tests.](image)

3. John-Cook Constitutive Model and Verification

3.1. John-Cook Constitutive Parameter Fitting

Johnson-Cook constitutive model takes into account the strain hardening effect, the strain rate effect and the temperature softening effect of materials under dynamic loading. It is suitable for describing the stress-strain ratio of most metallic materials under dynamic loading. Its mathematical expression (1) is

$$
\sigma = [A + B\varepsilon_p^m][1+C\ln(\dot{\varepsilon}^n)][1-(T^*)(\alpha^n)]
$$

where, $\sigma$ is the material stress; $\varepsilon_p$ is the equivalent plastic strain; $A$ is the yield point at the reference
temperature and quasi-static; $B$ is the hardening coefficient; $n$ is the hardening index; $C$ is the strain rate constant; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless equivalent plastic strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; $\dot{\varepsilon}$ is the plastic strain rate; $T^* = (T - T_{\text{room}})/(T_{\text{melt}} - T_{\text{room}})$ is the dimensionless temperature; $T$ is the current temperature; $T_{\text{room}}$ is the room temperature; $T_{\text{melt}}$ is the melting point of the material; $m$ temperature softening coefficient.

Based on the stress-strain relationship curves obtained from the quasi-static and dynamic experiments, the dynamic material relationship of 50SiMnVB steel is obtained from the mathematical expression of the Johnson-Cook constitutive model, as shown equation (2).

$$\sigma_y = [1036.15 + 1238.09\varepsilon_{ep}^{0.5982}] \left[ 1 + 0.0077 \ln \left( \dot{\varepsilon}^* \right) \right] \left[ 1 - (T^*)^{1.0534} \right]$$  \tag{2}

3.2. Constitutive Model Validation

To check the accuracy of the parameter adaptation of the Johnson-Cook constitutive model, the nonlinear finite element software Ls-dyna was used to numerically simulate the dynamic tensile test. The dynamic tensile process is simulated and the curves of the yield point and the plastic elongation ratio of the extracted material at the uniform deformation point of the tensile specimen are compared with the test results. The test conditions with a strain rate of 1700 s$^{-1}$ are selected for comparison and verification. The comparison between the test and simulation results is shown in figure 4. The dynamic constitutive model based on the quasi-static test is adjusted so that the relationship curve obtained by the simulation solution is slightly different from the curve based on the dynamic test results, but the error is small and capable. In order to meet the accuracy requirements of engineering calculations, the adapted material equation can better reflect the hardening properties of 50SiMnVB steel under dynamic loading.

![Figure 4](image-url)

Figure 4. Comparison of simulation and experiment results.

4. Fracture Behavior and Analysis of Two High-Strength Steels

4.1. Macro Fracture

The macroscopic properties of the tensile rupture at room temperature are analyzed. Figure 5 shows the comparison of the tensile fracture of 58SiMn steel at strain rates of 0.001 s$^{-1}$ and 1700 s$^{-1}$. It can be seen that the dynamic and static fracture form of 58SiMn steel is the same, the fracture plane is perpendicular to the axial tensile stress and the fracture mode is brittle.
Figure 5. Macroscopic fracture of 58SiMn steel under quasi-static and dynamic conditions.

Figure 6 shows the comparison of the tensile fracture of 50SiMnVB steel at strain rates of 0.001s\(^{-1}\) and 1700s\(^{-1}\). Fracture mode of the specimen under dynamic tensile loading is different. At 0.001s\(^{-1}\), the tensile specimen fracture is rough, which is a mixed tensile-shear fracture; at 1700s\(^{-1}\), the fracture is relatively flat and the fracture plane of 45 degrees to the direction of stretching, which is a pure shear fracture.

Figure 6. Macroscopic fracture of 50SiMnVB steel under quasi-static and dynamic conditions.

4.2. Microscopic Fracture

The macroscopic mechanical properties of materials are not only related to the stress-strain rate, but also closely related to the internal structure of the material. The most commonly used tool for fractional micromorphology analysis is an electron microscope. In the article, the MIRA3 scanning electron microscope is used to observe the fracture morphology of the specimen obtained. The micromorphology of the specimen fracture of 58SiMn steel under quasi-static and dynamic loading is shown in figure 7. From the SEM photos of the fracture surface of the specimen, the quasi-static and dynamic fracture morphology show similar microscopic properties. Judging from the fracture morphology under the low power lens, the fracture of the specimen is rough and has the characteristics of a brittle fracture; It can be seen from the fracture morphology of the high-performance lens that the main characteristics of the fracture are dissociation steps, micropores, and micropore fractures. The composition of the tearing edge formed by plastic deformation around the zone shows that the tensile fracture of 58SiMn steel is a mixed fracture mode in which toughness and brittleness coexist.

Figure 7. SEM image of 58SiMn steel under quasi-static and dynamic loading.
Figure 8 shows the microscopic morphology of the specimen fracture of 50SiMnVB steel under quasi-static and dynamic loading. It can be seen that the quasi-static and dynamic fractures of 50SiMnVB steel have the properties of tensile fracture and shear fracture. The surface of the tensile fracture is rough and the quasi-static and dynamic tensile fractures are quasi-split fractures. The area of the plastic deformation area of the dynamic tensile fracture is significantly reduced and the brittleness increased. The surface of the shear fracture is smooth and the quasi-static and dynamic shear fractures are split fractures. The surface of the quasi-static shear fractures has shallower pits and less toughness. Due to the microscopic properties of the tensile fracture of 50SiMnVB steel, 50SiMnVB steel is a tensile-shear mixed brittle fracture under axial tensile load. With increasing load-elongation speed, the tensile fracture component and the shear fracture component increase.

5. Conclusions
(1) Under quasi-static tensile load, 50SiMnVB steel has higher yield strength and tensile strength compared to 58SiMn steel; under dynamic load, the increase in the yield strength of 58SiMn steel remains unchanged, the plastic deformation capacity and the work hardening effect are improved. The yield strength and tensile strength of 50SiMnVB increases with increasing load-elongation speed and the ability to plasticly deform decreases, which shows the embrittlement properties under high-speed loading. With the same elongation rate, 50SiMnVB steel has higher strength and toughness.

(2) The constitutive J-C model of 50SiMnVB steel is fitted according to the stress-strain curve obtained from the test, which is verified by numerical simulation result. The finite element simulation confirms that the adapted equation can better describe the mechanical behavior of 50SiMnVB steel under a high strain rate.

(3) The failure modes of 58SiMn steel under quasi-static and dynamic axial tensile load are the same. The macro is a positive tensile brittle fracture and the micro is a quasi-split fracture. The 50SiMnVB steel is mixed under axial tensile load on tensile shear. With increasing load-elongation speed, the fracture mode is a pure-shear fracture mode. The microscopic fracture properties show 50SiMnVB steel is a tensile-shear mixed brittle fracture under axial tensile load. With increasing load-elongation speed, the tensile fracture component and the shear fracture component increase.

Acknowledgments
The authors thank the National Natural Science Foundation of China for financial support under Grant No. 12172380.

References
[1] Taylor G I 1963 The Fragmentation of Tubular Bombs Advisory Council on Scientific Research and Technical Development 5 (1) 202-320
[2] Hoggatt C R and Recht R F 1968 Fracture behavior of tubular bombs Journal of Applied Physics 39 (3) 1856-1862

[3] Stronge W J, Ma X and Zhao L 1989 Fragmentation of explosively expanded steel cylinders International Journal of Mechanical Sciences 31 (11-12) 811-823

[4] Zecevic B, Terzic J and Catovic A 2004 Influence of warhead case material on natural fragmentation performances Proc. of the 15th Int. DAAAM Symp. (Vienna: DAAAM International) pp 497-498

[5] Tanapornraweekit G and Kulirsirikasem W 2011 Effects of material properties of warhead casing on natural fragmentation performance of high explosive (HE) warhead World Academy of Science, Engineering and Technology 59 1275-1280

[6] Wilson L T, Reedal D R, Kuhns L D, Grady D E and Kipp M E 2001 Using a numerical fragmentation model to understand the fracture and fragmentation of naturally fragmenting munitions of differing materials and geometries 19th Int. Symp. of Ballistics pp 7-11

[7] Barnwal V K, Lee S Y, Choi J et al. 2021 On the fracture characteristics of advanced high strength steels during Hydraulic Bulge Test International Journal of Mechanical Sciences 190 106032

[8] Liang M, Li X and Lu F 2016 Modeling the dynamic fracture and fragmentation of explosive-driven metal ring with notches or grooves Archive of Applied Mechanics 87 (4) 1-15

[9] Li W B, Chen Z C, Wang X M et al. 2021 Research on the intermediate phase of 40CrMnSiB steel shell under different heat treatments Defence Technology 17(3) 1032-1041 (in Chinese)

[10] Zhao C, Wang S, Guo C et al. 2020 Experimental study on fragmentation of explosive loaded steel projectile International Journal of Impact Engineering 144 103610

[11] Shen Z X, Huang H D, Cen Z B et al. 2021 Natural fragmentation behavior of steel cylinders with variable charge geometries under detonation loading Combustion Explosion and Shock Waves 57 (2) 246-255

[12] Zhu J et al. 2018 Axial distribution of fragments from the dynamic explosion fragmentation of metal shells. International Journal of Impact Engineering 123 140-146