Experimental Study on Dynamic Tensile Properties and Ballistic Performance of Different Armor Materials

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Abstract. Hopkinson bar system was used to test the dynamic tensile properties of high nitrogen steel, 685 armor steel, 603 armor steel and 316 stainless steel by adjusting loading pressure, the strain rate and dynamic tensile strength of different armor materials were obtained. Under the experimental conditions in this paper, the dynamic tensile strength of the high-nitrogen steel is 1883 MPa which is the maximum of the four materials. At the same time, by using 12.7 mm armor-piercing projectiles, the ballistic tests of semi-infinite targets of different armor materials were carried out. Penetration depth of high-nitrogen steel is 25.5 mm which is the smallest of the four materials. The standard penetration depths of armor materials decrease with the increase of dynamic tensile strengths, and tensile strength increases under the test conditions in this paper. Therefore, the material with high dynamic tensile strength should be selected as the ballistic component in armor design.

Ceramic composite armor is mainly made of hard ceramic panel and metal or fiber composite material with good toughness for the back plate, which are usually bonded together with adhesives. By combining the brittle materials with high hardness and ductile materials with high strength, advantages of the two materials can be given full play, which can be used to meet the penetration resistance required by armors with high hardness and elastic modulus ceramic materials. Toughness and ductility of metal or fiber composite materials meet the requirements of armor impact resistance and anti-collapse ability, which has a good anti-ballistic effect[1-4].

Armor steels are most commonly used as metal backboard, which provide support for ceramics and absorb kinetic energy of projectile body and ceramic fragments. High toughness means strong energy absorption ability. When projectile penetrates target plates, metal backboard presents plastic deformation energy absorption, which can reduce the projectile's ability to continue to penetrate. Along with further penetration of projectile, metal backboard occurs plastic deformation to absorb lots of energy. However, damaging effects are caused by strong reflection wave for armored multiple elastic resistance is extremely adverse[5-7].
Four kinds of armors containing high nitrogen steel, 685 armor steel, 603 armor steel and 316 stainless steel were studied by testing dynamic tensile mechanical properties in this article to discuss the law of dynamic tensile mechanical properties. Ballistic test study of semi-infinite target of the four armors was carried to explore the relationship between dynamic tensile mechanical properties and elastic energy resistance, which provides experimental basis for the further application of armor materials.

1. Study on dynamic tensile properties of different armor steels
Dynamic tensile mechanical properties tests of high nitrogen steel, 685 armor steel, 603 armor steel and 316 stainless steel were carried out by using Hopkinson bar with φ16 mm for sample loading, and rod for high carbon chromium alloy steel. Incident bar is 1100 mm, the transmission rod is 1200 mm, the elastic modulus is 210 GPa, density is 7800 kg/m$^3$, the sample size is M8*1×20+φ4×10+ M8*1×20 mm. The thickness direction with the plate surface is in the same direction. Experiment equipment and sample are shown in Figure 1. The bullet length for dynamic tensile test is 300 mm.

![Figure 1. SHTB experimental apparatus and dynamic tensile specimens](image)

Martensitic aging steel bars were used to load the samples in the dynamic tensile tests of the four materials. The tensile conditions of different strain rates were realized by adjusting the loading pressure. Unidirectional dynamic tensile tests were carried out on four armor materials in the range of 0.5 to 1.7 MPa pressure in order to accurately obtain the dynamic tensile mechanical properties of different armor steels.

1.1. Dynamic tensile test and results of high nitrogen steel

![Figure 2. True stress-strain curves of high-nitrogen steel under different strain rates](image)
Figure 3. The dynamic tensile strength of high-nitrogen steel varies with strain rates

Dynamic tensile mechanical properties of high-nitrogen steel under pressure were tested by using Hopkinson tie-bar system with 3 samples in each group and 5 groups in total. Loading strain rate and dynamic tensile strength of each sample were obtained through analyzing and fitting the experimental data. True stress-strain curves of high-nitrogen steel under different strain rates are shown in Figure 2 under different dynamic tensile loading. It can be found that high-nitrogen steel is very sensitive to strain rate. The dynamic tensile strength of high-nitrogen steel varies with the strain rate as shown in Figure 3. When the strain rates are 510 s$^{-1}$, 976 s$^{-1}$ and 1341 s$^{-1}$, no fracture occurs during the loading process of high-nitrogen steel tensile samples, but when the strain rates are 1676 s$^{-1}$ and 1892 s$^{-1}$, all fracture occurs during the loading process.

1.2. Dynamic tensile test and results of 685 armor steel

Figure 4. True dynamic tensile Stress-strain curve of 685 armor steel under different strain rates

Figure 5. The dynamic tensile strength of 685 armor steel varies with strain rates
Hopkinson bar system was used on 685 armor steel with 5 groups in each set of 3 sample under the pressure of dynamic tensile mechanical properties test. We obtain loading strain rate of each sample and dynamic tensile strength of 685 armor steel through analysis of the test data fitting. Different strain rates of true stress-strain curve of 685 armor steel are showed in Figure 4. Figure 5 shows dynamic tensile strength of 685 armor steel with the change of strain rate. When the average strain rate of 685 armor steel is 863 s\(^{-1}\), the specimens appear all necking phenomenon, and when the average strain rate are 1182 s\(^{-1}\), 1487 s\(^{-1}\) and 1732 s\(^{-1}\), the tensile specimens break all. Dynamic tensile strength of the material increases with the increase of strain rate before broken, and does not change significantly with the strain rate after broken.

1.3. Dynamic tensile test and results of 603 Armor steel

![Figure 6. True dynamic tensile stress-strain curve of 603 armor steel under different strain rates](image1)

![Figure 7. The dynamic tensile strength of 603 armor steel varies with strain rates](image2)

Dynamic tensile mechanical properties of 603 armor steel were tested under air pressure with 3 samples in each group by Hopkinson bar system. The loading strain rate and dynamic tensile strength of each sample were obtained through analyzing and fitting test data. True stress-strain curve of 603 armor steel under different strain rates is showed in Figure 6. Figure 7 shows dynamic tensile strength of 603 armor steel with the change of strain rate. The aspect ratio of the specimen increases slightly when average strain rate of 603 armored steel is 588 s\(^{-1}\). But the tensile specimens fracture all when the average strain rate are 1135 s\(^{-1}\), 1545 s\(^{-1}\), 1842 s\(^{-1}\) and 2143 s\(^{-1}\). Dynamic tensile strength of the material increases with the increase of strain rate before the 603 armor steel material is broken, which does not change significantly after the material is broken and fails.
1.4. Dynamic tensile test and results of 316 stainless steel

![Figure 8. True dynamic tensile stress-strain curve of 316 stainless steel at different strain rates](image)

![Figure 9. The dynamic tensile strength of 316 stainless steel varies with strain rates](image)

Dynamic tensile mechanical properties of 316 stainless steel were tested under air pressure with 3 samples in each group by Hopkinson tie bar system. Loading strain rate and dynamic tensile strength of each sample were obtained through analyzing and fitting test data. True stress-strain curve of 316 stainless steel under different strain rates is showed in Figure 8, and dynamic tensile strength of 316 stainless steel varies with strain rates as shown in Figure 9. The sample doesn’t fracture when average strain rates of loading are 772 s\(^{-1}\), 1202 s\(^{-1}\) and 1556 s\(^{-1}\). But when strain rates of loading are 1838 s\(^{-1}\) and 2088 s\(^{-1}\), the samples fail. Dynamic tensile strength of 316 stainless steel increases with rising of strain rates.

2. Experimental study on the elastic resistance and dynamic tensile mechanical properties of different armor steels

Penetration resistance is an important performance of armor materials as a protective material, and to resist the penetration of projectiles, jets and fragments of different shapes and diameters is the main function. The armor is subject to dynamic load due to the instantaneous interaction when projectile penetrates armors, and dynamic mechanical property of the armor material is main parameter to characterize the mechanical property. The usability and dynamic performance of armor material must be related to each other as two different characterization methods of the same material. Therefore, to establish the relationship between the usability and mechanical performance of armor materials is
actually to build the relationship between the elastic resistance and dynamic performance, which can provide the basis for the design of armor protection.

Dynamic tensile mechanical properties of four armor materials were obtained through the Hopkinson bar system above, including high-nitrogen steel, 603 armor steel, 685 armor steel and 316 stainless steel. 12.7 mm armor-piercing projectiles were fired by 12.7 mm ballistic gun for the four armor materials mentioned above, and the standard penetration deep target tests were carried out for the semi-infinite targets of the four materials. Targets were tested with a ballistic gun and armor-piercing projectiles as shown in Figure 10. The standard projectile velocity is $v_{st} = 818.4$ m/s. Shooting distance is 10 m during the target test.

![Figure 10. (a)12.7 mm ballistic gun; (b)12.7 mm armor-piercing projectiles](image)

| Serial number | Target board structure | Average bullet speed (m/s) | Standard penetration depth (mm) | Dynamic tensile strength (MPa) |
|---------------|------------------------|---------------------------|--------------------------------|--------------------------------|
| 1             | High nitrogen steel    | 828                       | 25.5                           | 1887                           |
| 2             | 685 armor steel        | 820                       | 28.5                           | 1783                           |
| 3             | 603 armor steel        | 813                       | 31                             | 1350                           |
| 4             | 316 stainless steel    | 825                       | 48.5                           | 800                            |

![Figure 11. Standard penetration depth of 316 stainless steel](image)

The standard penetration depths of 12.7 mm penetrating 685 armor steel, 603 armor steel, high-nitrogen steel and 316 stainless steel were obtained through target test. Ballistic test results are showed in Table 1, while photos of 316 stainless steel standard penetration target test are showed in
Figure 11. Standard penetration depth of 685 armor steel, 603 armor steel, high-nitrogen steel and 316 stainless steel is 28.5 mm, 31 mm, 25.5 mm and 48.5 mm respectively.

![Figure 11](image)

**Figure 12.** Relationship between dynamic tensile strength and standard penetration depth of homogeneous armor materials

Relationship between dynamic tensile strength and penetration depth was established by taking dynamic tensile strength of armor material as the usability and taking the standard penetration depth as the characteristic parameter. Figure 12 for armor materials’ dynamic tensile strength and standard penetration depth show that standard penetration depths of armor materials are reducing with increasing of dynamic tensile strength under test conditions in this paper, and elastic resistance increases too. So choosing materials with high dynamic tensile strength as ballistic component can preferred armor design.

3. Conclusions

(1) Dynamic tensile mechanical properties through Hopkinson bar were tested by adjusting the loading pressure for four armor materials to obtain loading strain rate and dynamic tensile strength of different armor materials within the loading pressure range of 0.5-1.7, including high-nitrogen steel, 685 armor steel, 603 armor steel and 316 stainless steel. Within the loading pressure range, the maximum dynamic tensile strength of high-nitrogen steel is 1883 MPa and the minimum dynamic tensile strength of 316 stainless steel is 800 MPa.

(2) 12.7 mm armor-piercing projectiles were sheet to conduct ballistic test research on semi-infinite targets of different armor materials. Penetration depth of high-nitrogen steel is 25.5 mm which is the minimum, while penetration depth of 316 stainless steel is 48.5 mm which is the maximum. Relationship between penetration depth and dynamic tensile strength of armor materials by 12.7 mm armor-piercing projectiles is in direct proportion under the test conditions in this paper.

(3) Standard penetration depth of armor materials decrease with increase of dynamic tensile strength for four armor materials indicating that the elastic energy of armor materials increase with the increase of dynamic tensile strength. Therefore, materials with high dynamic tensile strength should be selected as the ballistic component in armor design.

4. References
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