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Experimental Investigation on the Ballistic Performance of 45 Steel Metal Plates Subjected to Impact by Hemispherical-Nosed Projectiles*

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Abstract: A series of impact tests were conducted to investigate the ballistic performances of single-, double- and three-layered 45 steel plates subjected to impact by hemispherical-nosed projectiles which were made from 38CrSi and diameter was 12.7 mm, the impact velocities ranged from 240 m/s to 600 m/s. The multi-layered plates arranged in various combinations of the same total thicknesses were normally impacted with the help of a gas gun. The initial and residual velocities of the projectiles were measured, and also the ballistic limit velocity for each configuration target was obtained and compared based on the investigation of the effect of the number of layers on the ballistic resistance. The results indicated that the ballistic limit velocity of multi-layered plate was higher than that of monolithic plate. The dominant failure model of monolithic plate was shearing, but the dominant failure models of multi-layered plate were global dishing and local bulging. Moreover, the failure models of plates of multi-layered plates were in relation to their order.

Key words: projectile; perforation; target; ballistic limit

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1 Introduction

It is of practical interest to enhance the structure's protective performance against projectile penetration in military and civilian applications. The method which is of the same or lower weight and price while of the same or better ballistic resistant property is promising. When a monolithic plate is replaced by multi-layered thin plates, the ballistic resistance of various configuration targets may be different resulting from changing the failure model. Although a lot of investigations have been conducted on the study of perforation resistance of monolithic plates experimentally, numerically, and theoretically, however, limited studies on multi-layered metal shields are reported in the published literature[1], and the results are to some extent incompatible.

It can be concluded from previous researches[2-10] that even though different aspects of the impact problem have been studied in previous experimental, analytical and numerical investigations, but the protection effectiveness of multi-layered shields remain a subject of controversy. It follows that the problem is not yet fully solved, and also there still remain a need for a systematic study on the impact

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behavior of layered plates.

In the connection, an interesting question can be posed: under projectiles impact what type of a shield would be superior in the perforation resistance to other structure targets of the same weight and total thickness? The differences in target capacity among various configurations can be related to the transition in deformation mechanism and failure model, a series of impact tests were conducted to investigate the ballistic performance of single, double and three in-contact layered plates in order to understand that under projectiles impact what type of a shield would be superior in the perforation resistance.

2 Experimen

2.1 Experimental Setup

The impact experimens were conducted in a two-stage compressed gun at Hypervelocity Impact Research Center in Harbin Institute of Technology, as shown in Fig. 1.

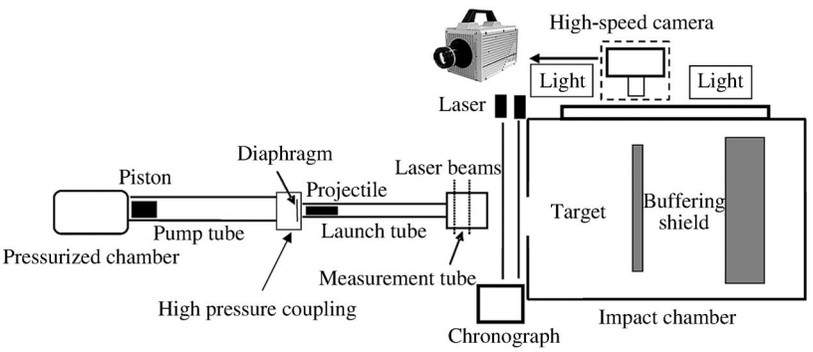


Fig. 1 Schematic of two-stage gas gun experimental system

A digital high-speed camera was also employed to record the process of the projectile penetrating the target and the projectile motion. The select frame rate was 50 000 s^{-1}, so that a frame was taken every 20 μs and the resolution was 512×128 pixels. These settings were selected based on early testing and presented an optimal trade off between available lighting and the minimization of blur in the images. A high-speed camera system was also used for measurements. The most important feature was the possibility to obtain traveled distance, velocity and acceleration as a function of penetration time for the assumed rigid bodies. Before impact experimen, it is need to demarcate the distance for high speed camera, as shown in Fig. 2. The initial and residual projectile velocity was measured by this high speed camera system, the data obtained through Equation (1).

$$v = \frac{10\Delta M \cdot (L_1/L_2)}{(P_1 - P_2) \times 10^3/N} \tag{1}$$

Here, v: velocity, m/s; L_1: real length of calibration pole, cm; L_2: length of calibration pole in coordinate paper, cm; N: frame, f/s; P_1: the number of start photo; P_2: the number of end photo; ΔM: numbers of projectile flight from P_1 to P_2.

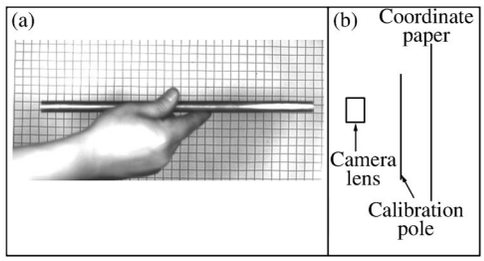


Fig. 2 Sketch of demarcate distance for high speed camera

2.2 Projectiles and Targets

The projectiles were made of hardened steel 38CrSi. After machining, they were oil hardened to a maximum Rockwell C value of 58 in order to prevent the plastic deformation during impact. Nominal

average hardness(HRC 55), diameter(12.7 mm) and mass(34.5 g) of the hemispherical-nosed cylinder projectiles were constant in all experimens. The geometry of projectile is shown in Fig. 3.

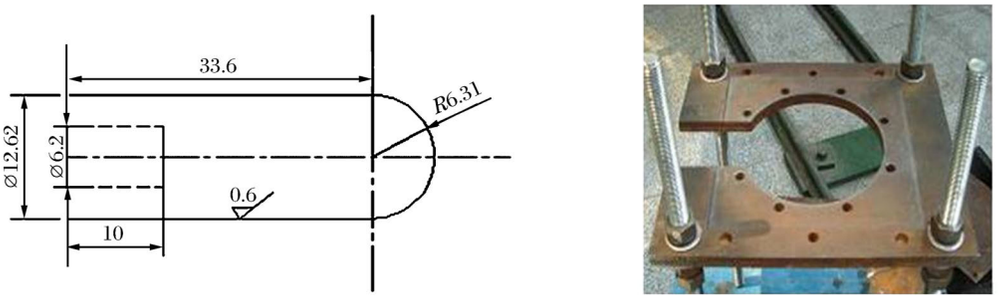


Fig. 3 Geometry and dimensions(in mm) for blunt projectile and target support

The target plates were made of 45 steel as a mild carbon alloy steel, whose yield stress is about 780 MPa after heat treatment. Square plates with a side of 230 mm were fixed to a thick mounting armor plate by means of 8 bolts arranged on a 170 mm diameter pitch circle in the target chamber, as shown in Fig. 3. The single layer plate is 6 mm thick and the thicknesses of layers of layered plates are 2 and 3 mm, respectively. For the investigation of the effect of the layering, three configurations are considered. In this study, the target code T3T3 indicates a in-contact double-layered plate whose layers' thickness are all 3 mm, T2T2T2 is a three-layered plate whose layers' thickness are all 2 mm, also T6 denotes a monolithic plate whose thickness is 6 mm.

3 Experimental Results

The ballistic limit velocity is an essential parameter in the energy balance equation of ballistic perforation, calculated as the average between the highest impact velocity not giving perforation and the lowest impact velocity giving complete perforation of the plate. The solid lines through the data points shown in Fig. 4 were fitted to an analytical model originally proposed by Recht and Ipson[11]

$$v_r = a\,(v_i^p - v_{bl}^p)^{1/p} \tag{2}$$

The ballistic limit velocity v_{bl} is always taken on the basis of the experimental data, both a and p, v_{bl} are fitted to the experimental results using the method of least squares. The values of a, p and v_{bl} obtained from the experimental data are given in Table 1.

Table 1 Ballistic limits and model constants of targets against projectiles

Target code	a	p	v_{bl}/(m/s)
T6	0.9	2.08	305
T3T3	0.78	2.5	343
T2T2T2	0.93	205	352.5

Based on the result of impact experimens, the residual velocity versus the initial velocity curves of the projectiles are constructed, as shown in Fig. 4.

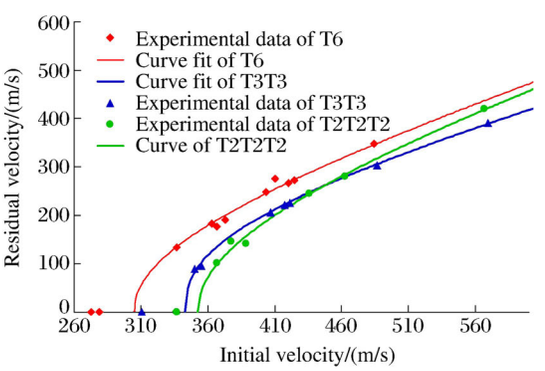


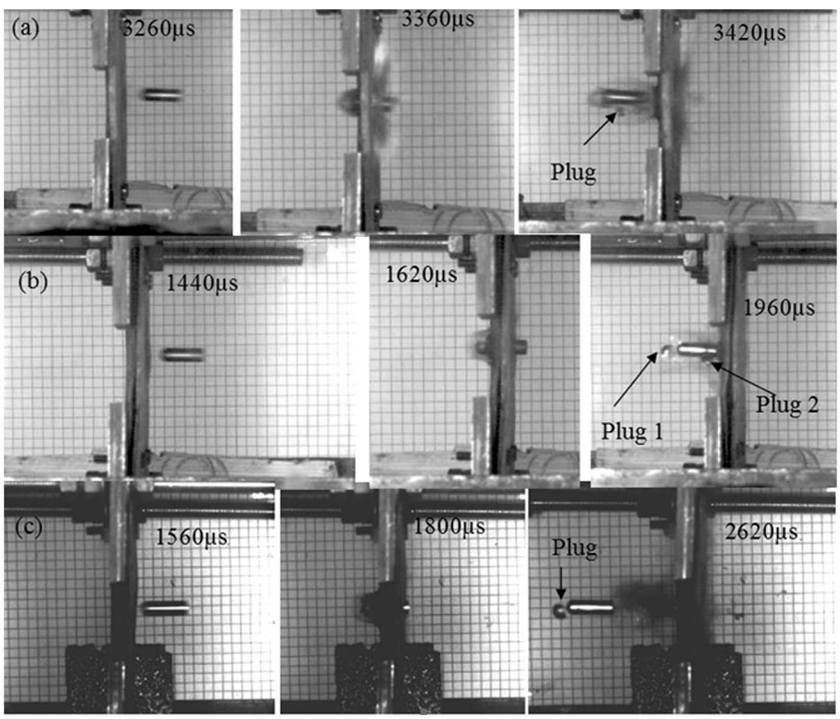
Fig. 4 Residual velocities versus initial velocities for targets

Seen from Fig. 4 and Table 1, the ballistic limit velocity of T6 is 305 m/s, and that of T3T3 is 343 m/s, also that of T2T2T2 is 352.5 m/s. T2T2T2 presents

slightly more ballistic resistance than T3T3, only acquiring an increment of ballistic limit velocity about 2.77%, but a increment 15.57% is found as T2T2T2 compared with T6. Therefore, it can be concluded that the ballistic limit velocity is enhanced when using layered plates instead of monolithic plates. Moreover, the ballistic limit velocity of target increases with increasing the number of layers, and also the effect of layering decreases with the increasing impact velocity of projectile.

4 Failure Mechanisms

High-speed camera images from some experimens are presented in Fig. 5. As shown, some targets failed by plugging. Moreover, the projectile may rotate somewhat in the cavity during penetration even though both pitch and yaw are small due to an unsymmetrical failure model.



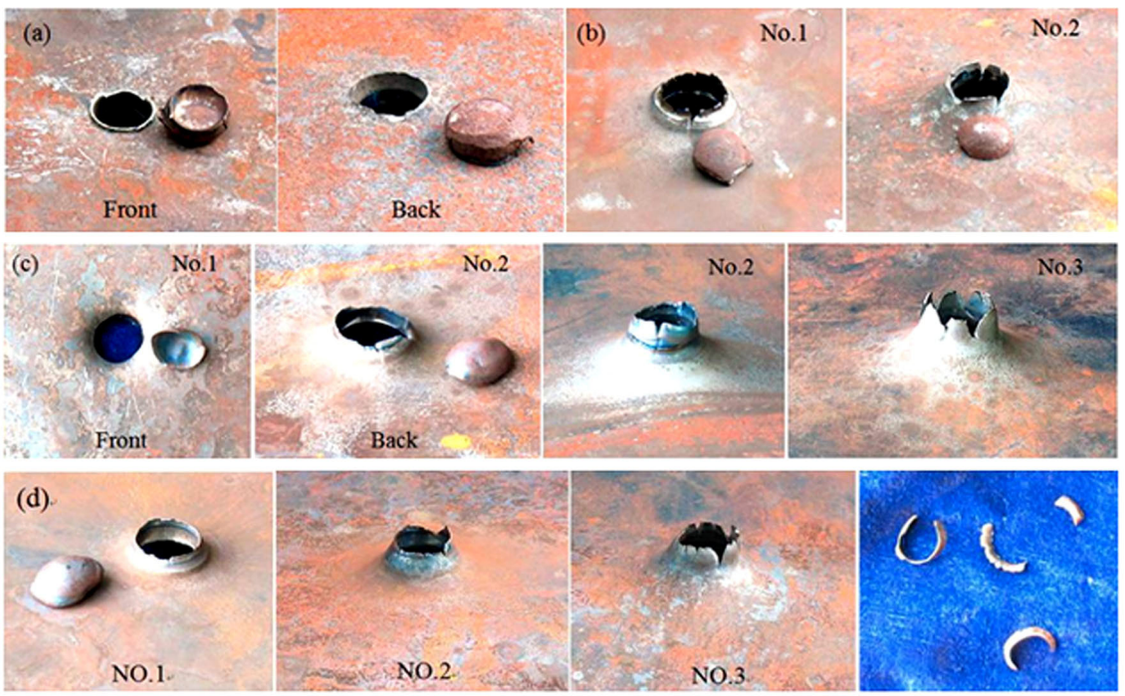
(a) T6, v_i=403.82 m/s, v_r=247.80 m/s; (b) T3T3, v_i=350.36 m/s, v_r=88.76 m/s; (c) T2T2T2 v_i=367.11 m/s, v_r=100.95 m/s

Fig. 5 Some high-speed camera images from experimens

Corresponding targets and plugs are shown in Fig. 6, note that the No. 1, No. 2 and No. 3 are the order numbers of plates in layered plate, and also the "front" denotes the impact side of plate. For monolithic plates, the plugs are seen to be both smooth and cylindrical. It is noticed that the plugs have a significant bulge on the distal side, and a variable shear zone height was observed on the surface of the plug, as shown in Fig. 6(a). The dominant failure model is shearing that the global deformation can be negligible, where failure is caused by plugging due to intense shear localization. It should be noticed that the frontal side of plate is smooth while the rear side is coarse, as depicted in second picture in Fig. 6(a). The photographs reveal that after the first indentation of the projectile that a stage of compression, then the critical damage of the plate is rapidly achieved and cracks start to grow in front of projectile. The cracks propagate toward the rear side of the plate, and then a plug is formed.

Relating to the double-layered plates, two plugs are detected and the plates are not simply shearing, and also the global deformation seems to be somewhat larger than monolithic plates. The figure shows that projectiles cause failure by plugging due to stretch and bend the material in contact with projectile, resulting in a cut circular indentation in the plate, and also cracks are detected near the

indentation, thinning before fracture can be clearly observed in the first plate. The size of the circular cap plug is slightly smaller than that of the indentation, and also obvious plastic deformation of plate is detected. It is also seen that the second plate(Plate 2) deforms much more than the first plate(Plate 1) for the double-layered plates, since it is much harder to localize the deformation in Plate 2(causing global bending and stretching). Some petals on the rear side are seen, as shown in Fig. 6(b).



(a) T6, v_i=403.82 m/s, v_r=247.80 m/s; (b) T3T3, v_i=350.36 m/s, v_r=88.76 m/s;
(c) T2T2T2 v_i=367.11 m/s, v_r=100.95 m/s; (d) T2T2T2 v_i=566.40 m/s, v_r=420.20 m/s

Fig. 6　Deformed plates and plugs after impacted by projectiles

For the configuration of T2T2T2, the first plate(Plate 1) is squeezed and deforms outwards, cause failure by plugging due to stretching and thinning the material in contact with projectile, tiny cracks are detected near the indentation. After some time, the projectile and the third plate squeeze the second plate, sometimes making a ring of material clearly seen in the plate, as shown in Fig. 6, and also ejected from the plate when the velocity of projectile is high, as shown in Fig. 6. In last, the projectile perforates the Plate 3, the material is pushed aside and large petals are formed. It is also seen that the second plate deforms much more than the first plate, since it is much harder to localize the deformation in Plate 2(causing global bending and stretching), the same for Plate 3 compared to Plate 2. From above discuss, it reveals that the failure models of plates depend on the set-up of layers. For example, the main failure models in the first layer are bulging and pluging as a result of bending and stretching. Whereas the dominant plate models in the second and the third layer are a combination intense bulging, petaling and dishing that the result is region of membrane stretching, bending and tearing. Moreover, some petals are found on the tip of the cavity, the cracks of the third layer are larger and the number of petals is smaller but their sizes are greater than those of the second layer.

A failure model with higher energy absorption can significantly improve the ballistic resistance of a shield. The dominant failure models change from shearing to tensile stretching and bending which absorb more kinetic energy of projectile when using multi-layered plates instead of monolithic plates, namely, the bending and stretching action can be enhanced and thus the multi-layered plates may undergo considerable deformation before fracture. Thereby, the ballistic limit velocities of multi-layered plates are higher than those of monolithic plates.

5 Conclusions

The perforation behavior of monolithic and layered steel plates impacted by hemispherical-nosed projectiles based on the impact tests, and also the influence of the numbers of layers on the ballistic resistance were studied. Main conclusions can be drawn from the results that the number of layers significantly affects the ballistic resistance of layered plates. The layered plates were more effective than monolithic plates under impacted by hemispherical-nosed projectiles, and also the ballistic limit velocity increases with the increasing number of layers. Furthermore, the effect of layering decreases with the increasing impact velocity of projectile.

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45 钢板对半球形头弹的抗穿甲特性研究

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摘要: 利用轻气炮进行了 38CrSi 半球形头杆弹正撞击 45 钢板的撞击实验, 研究了单层板、等厚接触式双层板和 3 层板对直径为 12.7 mm 弹体的抗穿甲性能。通过实验得到了这几种结构的初始-剩余速度曲线以及弹道极限, 研究了分层数目对叠层靶抗侵彻性能和失效模式的影响。研究结果表明, 多层板的弹道极限高于等厚单层板, 单层板主要失效模式为剪切, 而多层板的主要失效模式为整体的蝶形变形和局部的盘式隆起。对于多层板, 靶板具体的失效模式与其在靶中位置相关。

关键词: 弹体; 穿甲; 靶体; 弹道极限

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