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# Study on Characteristics of Partial Penetration of Projectile into Steel Panel*

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**Abstract**: Study on partial embedment of projectile (PEP) is put forward with the development of modern science and technology. The outer part of PEP standing stably can form an obstacle or induce the selective object to attack it by waiting for the proper chance, or act as the loading point to realize the special application. The research on a new nose shape projectile was carried out by the numerical analysis on process and characteristics of PEP and material testing of rheological behavior. Meanwhile, the main dimensionless group parameters were obtained by dimensional method. The deformation of target and energy evolution of the whole system in the forward and rebound phases of projectile were analyzed. The exploratory development work on mechanics of the PEP action was performed. Ultimately, PEP on steel panel was verified by artillery experiment.

**Key words**: partial embedment of projectile (PEP); steel plate; experimental study; numerical simulation

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## 1 Introduction

With the development of science and technology, partial embedment of projectile (PEP) can form an obstacle or induce the selective object to attack it by waiting for the proper chance, or act as the loading point to realize the special application. Here PEP refers to part of projectile embeds in the target and the other stand out which based on the partial penetration of projectile.

The study of the impact of projectile on targets has a long history of two and a half centuries or so. Plenty of work on penetration effect of projectile and characteristics of resistance of penetration had been carried out by many scholars[1-3]. Recently non-ideal projectiles impacting on targets are reviewed by Goldsmith[4], the majority are with regard to the ballistic deflection and ricochet of projectile at oblique and yaw impact. Of great reference value is the phase diagram of projectile impact target in the references of Backman and Goldsmith[3,5]. Ballistic limit curve and projectile states including perforation, embedment, and ricochet were obtained with conditions of projectile and target material, projectile geometry and target thickness. But this study is only a summary on the experimental phenomena under given conditions and cannot reveal the mechanism of partial embedment of projectile (PEP). It is necessary to

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perform the further work. On the other hand, different from the above concept of embedment, here PEP means projectile embed in target and partial projectile is out of target. The traditional geometry projectile is prone to rebounding and perforating. So in this paper a new nose shape projectile would be studied. The preliminary mechanics is got by means of numerical simulation, material testing of rheological behavior and artillery experiment, etc.

## 2 Problem Description

As shown in Fig. 1, projectile penetrating partially finite thickness metallic target vertically is studied. The length of model projectile is about 300 mm, its diameter is one fifth of projectile length, the nose length is one third of projectile length or so, mass of projectile is about 5 kg. The target thickness is 40 mm. Materials of projectile and target are respectively 30CrMnSiNi2A and 10CrNi3MoV.

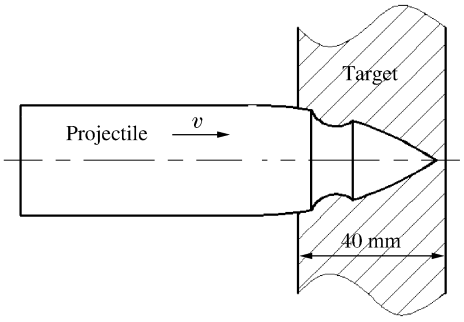



Fig. 1 Sketch of projectile penetrating target

## 3 Numerical Simulation

In order to analyze the PEP, the action and course of PEP on target are studied with the help of numerical simulation technique provided by nonlinear finite element software. The emphasis of research work is mainly laid on the evolvement of velocity, displacement and acceleration of projectile versus time, energy and deformation of target close to the groove region. The axisymmetrical mode is used to simulate because of the symmetry of the vertical penetration.

### 3.1 Computational Model and Model Parameters

The material of projectile 30CrMnSiNi2A is high strength steel. It possesses high hardness and good ductility by heat treatment and is used extensively as an impactor. So projectile with 30CrMnSiNi2A deforms hardly in low-velocity penetration experiments. In simulation, the projectile is assumed as a rigid body. The density of projectile $\rho$ is 7 850 kg/m$^3$, the Yong's modulus $E$ is 210 GPa, and the Poisson ratio $\mu$ is 0.28. Material of target is 10CrNi3MoV. It is with finely ductile. The Johnson-Cook constitutive model[6] is used for target steel, and it can describe the material dynamic behavior from low strain rate to high strain rate. This model considers linear thermo-elasticity, the von Misses yield criterion, the associated flow rule, isotropic strain hardening, strain-rate hardening and softening due to adiabatic heating. It is valid for metals subjected to large strains, high strain rates and high temperatures, and can well describe target material deformation of impact. The main parameters of target material are listed in Table 1.

**Table 1 Main material parameters of target used in calculations[7]**

| $\rho$ /(kg/m$^3$) | $G_s$ /(GPa) | $\mu$ | $T_{room}$ /(K) | $T_{melt}$ /(K) | $A$ /(MPa) | $B$ /(MPa) | $n$ | $C$ | $m$ |
|---|---|---|---|---|---|---|---|---|---|
| 7 800 | 77.9 | 0.33 | 298 | 1 763.5 | 898.6 | 356 | 0.586 | 0.022 | 1.05 |

### 3.2 Numerical Results and Analysis

Numerical simulations on partial penetration of projectile with groove structure nose at low velocity were carried out. The variation of the projectile velocity and displacement versus time were analyzed, as well as the deformation of target material near the groove structure. Fig. 2-Fig. 4 are the displacement,

velocity and acceleration of projectile respectively. Fig. 2 shows that the projectile does not perforate target and its displacement began to decrease slowly after reaching maximum due to the elastic recovery of target. Fig. 3 indicates that the projectile velocity decreases with the process of the penetration firstly and then increases inversely when its value reaches zero. However, when the velocity reaches the inverse maximum, it begins to decrease. The final velocity reaches zero, which indicates that the projectile successfully embeds in the target. Similarly, Fig. 4 shows that the axial overload of projectile soars to the maximum of 65 000$g$ or so, and then declines to zero quickly, following that the negative acceleration appears due to the target material resistance, thus the increase of the projectile velocity is held back. The curves of kinetic energy of projectile and internal energy of target with time are shown in Fig. 5. From the kinetic energy curve of projectile, we can conclude that projectile undergoes the huge resistance force at the initial stage, which makes its kinetic energy rapidly decrease to zero. After that, the projectile recovers part of kinetic energy because of the target elastic recovery. Finally, the kinetic energy becomes zero due to the hindrance of target material close to projectile groove. At the same time, the internal energy of target soars at the first stage, and reaches the climax value when the projectile's kinetic energy reaches zero. But its maximal value is less than the initial kinetic energy of projectile. It also shows that the most part of the initial kinetic energy is converted into the internal energy of target.

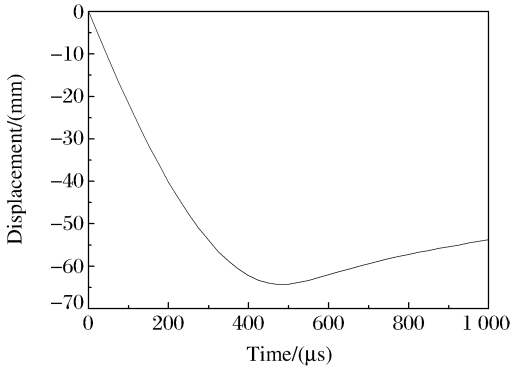



Fig. 2 The projectile displacement versus time of partial penetration

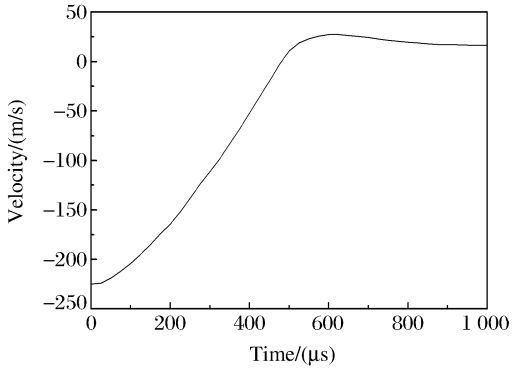



Fig. 3 The projectile velocity versus time of partial penetration of projectile and target

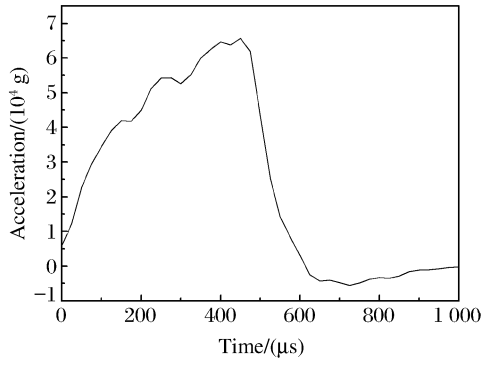



Fig. 4 The projectile acceleration versus time of partial penetration

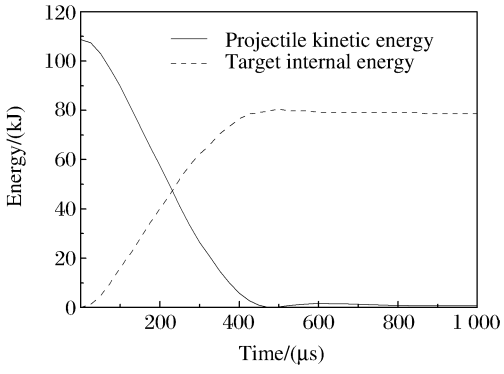



Fig. 5 Curves of energy versus time of partial penetration of projectile and target

The deformation of target material around projectile groove is given in Fig. 6 and Fig. 7. Fig. 6 indicates that projectile is belong to the forward phase of penetrating target, from which it shows that the target material clings to the upper part of projectile groove, but has a gap for the lower part of

projectile groove. As shown in Fig. 6, the horizontal grid line bends to the direction of penetration, the closer to projectile surface, and the greater of the deflection. This indicates that the motion of projectile makes the target material around it move forward along the penetration direction. The contrary conclusion is obtained for the target material clings to lower part during rebound process, as shown in Fig. 7.

Fig. 8 is the velocity vector of target close to groove region at 450 μs. It shows that the direction of projectile velocity vector is gadarene in the forward phase of projectile, and that of target material nearby projectile is same. The value of projectile velocity is larger than that of target element, the smaller of the distance between the element position and projectile, the larger of the velocity of target element. Fig. 9 is the velocity vector of groove region at 675 μs. It shows that velocity vector of projectile is upturned in the rebound phase, and that of target material nearby projectile is same, too. The value of projectile velocity is also larger than that of target element, the smaller of the distance between element position and projectile, the larger of the velocity of target element. Correspondingly, Fig. 10 shows the micro-rheological characteristics of positions (Points of *A* and *B* showed in Fig. 9) close to and far from groove region. Fig. 10(a) shows that the direction of rheological lines is same with penetration direction. But the direction of rheological lines as shown in Fig. 10(b) is different from that shown in Fig. 10(a). Comparing with rheological lines among different positions, the rheological lines in Fig. 10(a) are denser than that of Fig. 10(b). This indicates that simulation result is in good agreement with the microscopic test.

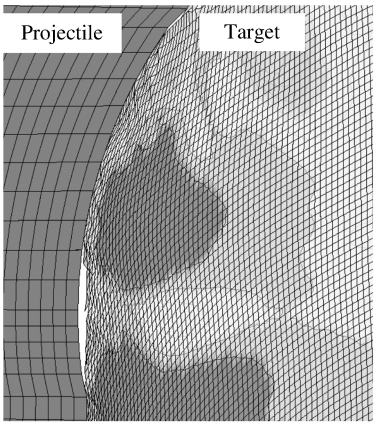



Fig. 6 Deformation of target close to groove region in the forward phase of projectile

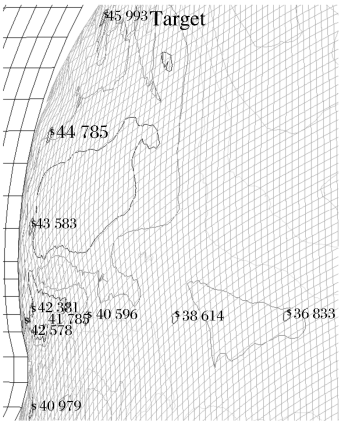



Fig. 7 Deformation of target close to groove region in the rebound phase of projectile

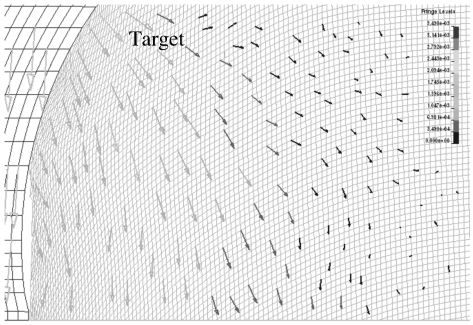



Fig. 8 Velocity vector of target close to groove region (Forward direction, $t$=450 μs)

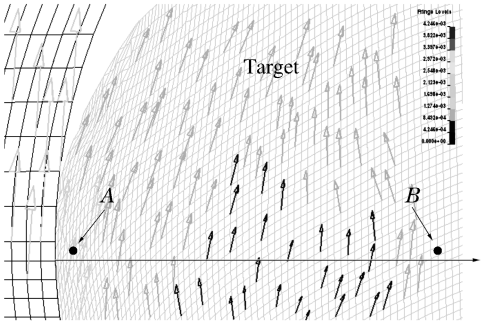
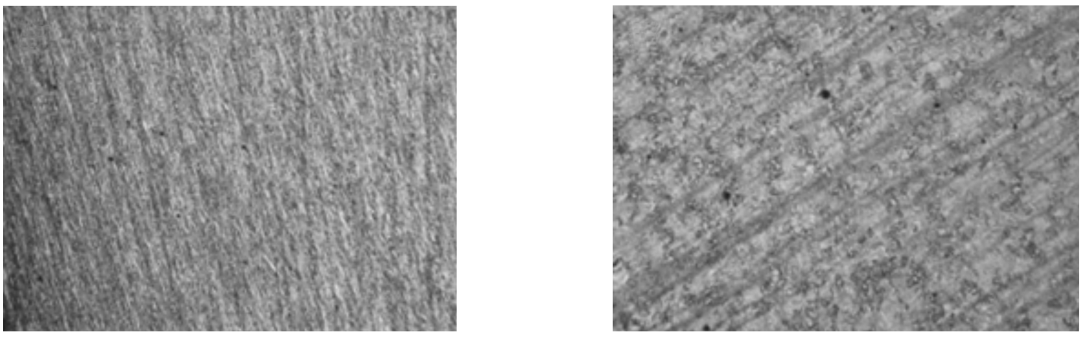



Fig. 9 Velocity vector of target close to groove region (Rebound phase, $t$=675 μs)



(a) Close to groove at $A$ point　　(b) Far from groove at $B$ point

Fig. 10　Micro-rheological characteristics(Points of $A$ and $B$ showed in Fig. 9)

Fig. 11 shows that curves of the internal energy density of element nearby projectile increase rapidly and don't change until projectile rebounds, then internal energy density of these elements increase to maximum again and keep a constant value, the closer of distance between target element and projectile surface, the more obvious of this variation. But the secondary increase of internal energy density is not obvious for element far away from projectile surface. Fig. 12 shows the secondary increase of internal energy density observed for all elements nearby projectile surface, only the time of secondary increase is different.

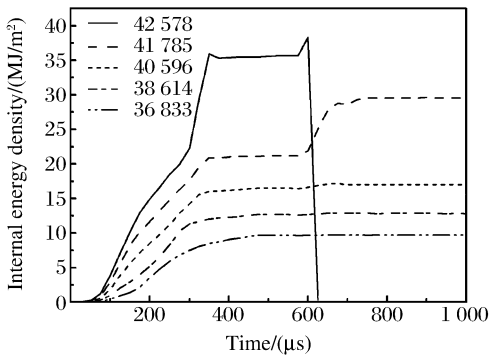



Fig. 11　Internal energy density versus time of target elements in radial direction (Positions of elements showed in Fig. 7)

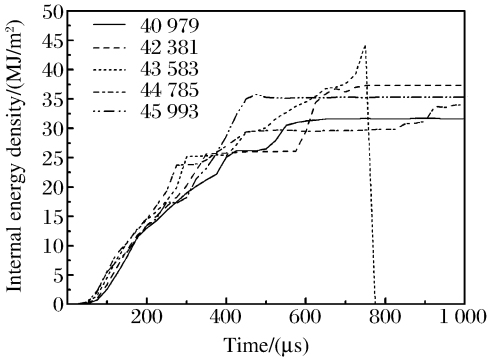



Fig. 12　Internal energy density versus time of target elements in axial direction (Positions of elements showed in Fig. 7)

## 4　Dimensional Analysis of PEP

In this section, the relationship of PEP striking velocity band with the geometric structure and material performance of projectile and target would be analyzed with the help of dimensional method.

Take the vertical penetration for instance, supposed projectile is rigid and target is elastic-plastic under the condition of the strength of projectile far superior to that of target. So the PEP sticking velocity band $\Delta v_{cr}$ is mainly determined by

$$\Delta v_{cr} = f(\rho_p, E_p, \mu_p, N, L_p, D_p; L_g, V_g, \rho_t, E_t, \mu_t, \sigma_t, H_t)$$

Where the subscripts p and t denote the projectile and target respectively, $\rho_p$ and $\rho_t$ the density, $E_p$ and $E_t$ the Yong's modulus, $\mu_p$ and $\mu_t$ the Poisson ratio, $N$ the nose shape factor, $L_p$ the projectile length, $D_p$ the projectile diameter, $L_g$ the characteristic size of relative position of groove, $V_g$ the groove volume of projectile, and $H_t$ the target thickness.

It is selected the fundamental quantities of $\rho_p, D_p, \sigma_t$, to make dimensionless analysis as follows

$$\frac{\Delta v_{cr}}{\sqrt{\sigma_t/\rho_p}} = f\left(\frac{E_p}{\sigma_t}, \mu_p, N, \frac{L_p}{D_p}; \frac{L_g}{D_p}, \frac{V_g}{D_p^3}, \frac{\rho_t}{\rho_p}, \frac{E_t}{\sigma_t}, \mu_t, \frac{H_t}{D_p}\right) \tag{1}$$

The above item $V_g/D_p^3$ of Eq. (1) can be transformed into the form of $E_{tg}/E_p$ by the following Eq. (2). Where $E_{tg}$ is the deformation energy of target material which squashed in the groove structure, and $E_p$ is the kinetic energy of projectile respectively.

$$\frac{V_g}{D_p^3} \rightarrow \frac{V_g}{D_p^3} \cdot \left(\frac{v_c}{\sqrt{\sigma_t/\rho_p}}\right)^{-2} \rightarrow \frac{\sigma_t V_g}{\rho_p v_c^2 D_p^3} \rightarrow \frac{E_{tg}}{E_p} \tag{2}$$

When only changing the parameters of projectile groove and other parameters keep constants, the dimensionless $\Delta v_{cr}$ is

$$\frac{\Delta v_{cr}}{\sqrt{\sigma_t/\rho_p}} = f\left(\frac{L_g}{D_p}, \frac{E_{tg}}{E_p}\right) \tag{3}$$

The above Eq. (3) shows that the velocity band of PEP is influenced by the relative position of groove $L_g/D_p$, the energy relative value of $E_{tg}/E_p$ and the material properties of target. Consequently, unlike the conventional penetration of projectile, PEP is dependent on the striking velocity of projectile, and the groove structure and the material dynamic parameters of target.

## 5 Experimental Verification

Based on the above analysis, the artillery experiments of the new nose shape projectile vertically partial penetrating target were carried out. The material and geometry structure of projectile and target are taken the same with that of the part numerical simulation. The typical experimental photo is showed in Fig. 13. It shows that the projectile nose embeds in target firmly by using the groove structure, and the partial embedment of projectile (PEP) is verified. The result indicates that, comparing with the penetration rebound of conventional projectile, the groove structure of projectile nose can play an important role in eliminating effectively the rebound from target.



Fig. 13 Experimental photo of PEP

## 6 Summaries

Based on the new nose shape, partial embedment of projectile (PEP) is verified. The preliminary mechanics is carried out by different means. The curves and physical images are got with the help of the computational analysis. The micro-rheological features are obtained for different positions of target by material microscopic testing. The main dimensionless group parameters are obtained from dimensionless analysis and the direct results are gained by artillery experiment. It shows that it is the key on the changes in material flow, deformation of material and the proper distribution of energy during the penetration process. A further study work would be performed in the near future.

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# 弹丸对钢板的半侵彻作用特性研究

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**摘要**: 随着现代高新技术的发展提出了对弹丸半侵彻(PEP)的研究,通过弹丸的半侵彻作用使其稳定嵌立于目标靶上,并由其外露部分形成障碍或感应目标伺机作用、或作为受力承载点等方式实现特殊用途。针对新结构弹头开展了弹靶半侵彻过程的数值模拟和靶材流动特性研究,采用量纲理论获得了弹丸半侵彻靶板的主要无量纲组合参量,获得了弹丸侵彻与反弹阶段靶板形变与弹靶系统能量分配特性,并对半侵彻作用机理进行了初步的探讨。最后通过炮射实验验证了实现稳定嵌立于靶板的可行性。

**关键词**: 弹丸半侵彻;钢板;实验研究;数值仿真

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