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The Depth Model of the Cratering Stage of Shaped Charge Jet Penetrating into Targets

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ABSTRACT

To get the depth model of cratering stage of shaped charge jet penetrating into targets, the penetration process on the target is studied through numeral simulation and experiment. Parameters of cratering stage in penetration into different targets, which are formed from TNT and LX-14 charge with the respective calibers of 56 mm and 82 mm, are obtained by numerical simulation. The depth model of the cratering stage of shaped charge jet penetrating into targets is built by data fitting. Both of the COMP B charge simulation and experimental validation are conducted. The results show: the error between the calculated value and simulation value based on depth model is 4.6% and the error between theoretical value and experiment value is 4.8%, which indicates that the model can be used to calculate the depth of the cratering stage of jet penetrating into targets.

Keywords: *shaped charge jet; numerical simulation; cratering stage; penetration length; penetration diameter*

1. INTRODUCTION

Penetration of shaped charge jet can be divided into cratering, quasi-steady, and termination stages. The ratio of energy consumption against penetration depth in the cratering stage is much larger than that in the quasi-steady stage and termination stage[1]. Repeated cratering is one main factor for a multi-layer target to

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effectively attenuate shaped charge jet penetration[2]. Therefore, the determination of parameters of the cratering stage of jet is a significant basis for the design of the multi-layer target.

Study on the cratering stage of shaped charge jet in the existing literatures is mostly based on qualitative analysis. Literature [3-4] indicates that, at the beginning of penetration, the jet head hits a steady target and then produces pressure with millions of atmospheric pressure. Shock waves transmit from the collision point to the target and shaped charge jet, dregs of the target and shaped charge jet splash, and the shaped charge jet builds three high zones in the target. This stage only accounts for a tiny part against the total penetration depth. Zhang Junkun[5] analyzed changes of the penetration pressure during jet penetration, determined the depth of the cratering stage, and verified the theory raised by Wang Zhenyu[6] that the corresponding penetration depth of the cratering stage is approximately times of jet diameter. Sun Gengchen[7-8] researched an experiment on cratering caused by a high-speed projectile colliding a thick metallic target, concluded the experiment result through dimensional analysis, and gained the empirical relationship of the ratio of the depth of cratering stage against bullet diameter. However, such empirical formula cannot be directly used to calculate the depth of cratering stage of shaped charge jet penetrating into the target, but only applies to cratering of super high-speed bullet.

The change rule of the pressure at the interface between shaped charge jet and the target is analyzed by means of numerical simulation, and the cratering stage and quasi-steady stage of the shaped jet penetration are effectively distinguished. Afterwards, depths of cratering stage of TNT and LX-14 charge with the respective calibers of 56 mm and 82 mm in penetration into different targets are obtained through simulation. The formula of the depth of cratering stage of the projectile in [7,8] literatures are amended through data fitting and a model of the depth of cratering stage of shaped charge jet penetrating into target is built. Finally, the model is compared with the numerical simulation result of COMP B charge and experimental result, verifying the correctness of the depth model of the cratering stage.

2. NUMERICAL SIMULATION

2.1 Building of the simulation model

AUTODYN software is used for numerical simulation, which simplifies the simulation model to be a two-dimensional axisymmetric model, with the classic model structure shown in Figure 1. The charge material in the model is RDX-2, with the charge diameter of 56 mm and charge height of 93.3 mm. Point initiation is used and the stand-off is 80 mm. The shaped charge liner is coneshaped, with the cone angle of 60°and the wall thickness of 1 mm, and it is made of copper. The target is a 45 steel cylinder, with the diameter of 100 mm and the height of 180 mm. Lagrange model is used on the target and Euler model is used on other materials. The material models and state equation parameters are shown in [9-10] literatures.

On the initial 80 mm target on which the shaped charge jet flows, observation points are set every other 1 mm. when the shaped charge jet flows through these measuring points, the density, velocity, and pressure, etc. of the micro unit of material will be recorded. Upon the completion of numerical calculation, material performance is visually and quantitatively analyzed by the use of data processing.

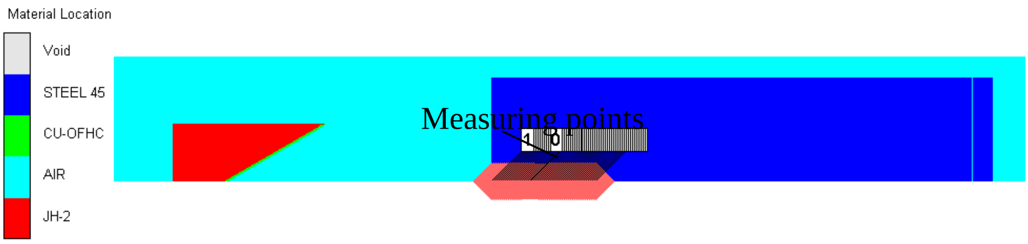

Fig.1 The overall structure of simulation model

2.2 Determination of parameters of the cratering stage

The variation of the measuring points' pressure vs time is calculated by the use of the built model, which is shown in Figure 2. It can be seen from the figure that the impact pressure on the target at the time when the shaped charge jet impacts the target can reach 253 GPa, which is maximum value throughout penetration. Under the influence of the unloading wave on the target surface, the target material flows sharply at the beginning of impact, and the pressure also changes greatly. This is the unsteady cratering stage, as shown in the stage before 29 μs in the figure, with the depth of the cratering stage about 6 mm. Afterwards, the penetration interface is far from the free surface of the target. Therefore, the unloading influence of the free surface can be ignored. Next, it goes into the quasi-steady penetration stage since the shaped charge jet continuously impacts the target and the material flow tends to be steady, with the pressure on the impact interface of 60~70 GPa, as shown in the stage after 29 μs.

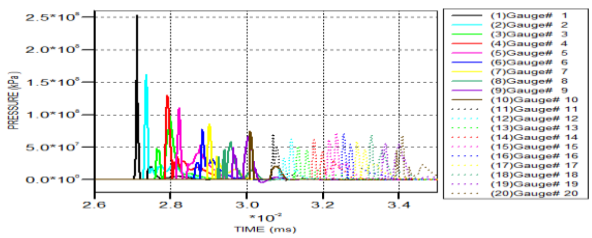

Fig.2 Variation of the measuring points' pressures with time

Two important parameters including jet tip diameter and tip velocity at the time of impact are also obtained through numerical simulation. Figure 3 shows the simulation result at 27 us. It can be seen from the figure that the jet tip presents a mushroom hairstyle when touching the target and the average value of tip diameter is used as the tip diameter at the time of impact; the jet tip velocity is also not a definite value and the maximum velocity of 5,570 m/s on the first measuring point is approximately regarded as the jet tip velocity at the time of impact.

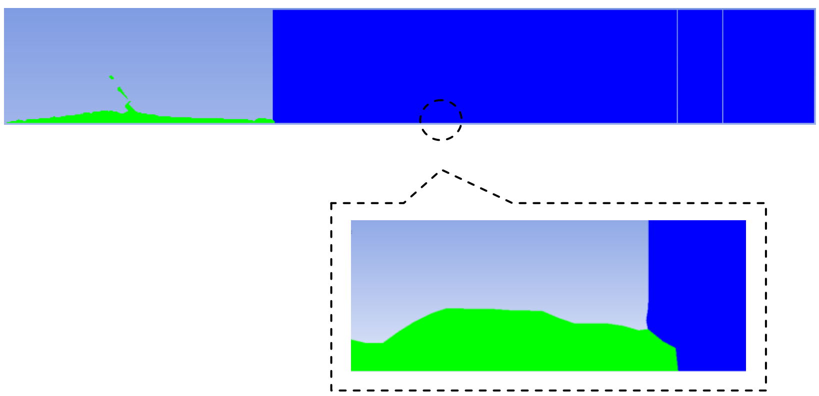

Fig.3 The diameter of jet tip at the time of impact

2.3 Calculation result and analysis

TNT and LX-14 shaped charge with the calibers of 56 mm and 82 mm are respectively penetrated into standard homogeneous RHA, STEEL 1006, COPPER, and ALUMINUM targets by means of the afore-said numerical simulation. Through research, depths of the cratering stage, jet tip diameter and velocity at the time of impact are obtained, with the calculation result as shown in Table 1 and Table 2.

Tab.1 The calculation conditions and results of TNT charge

Example	Charge caliber (mm)	Target material	Jet tip velocity at the time of impact (m/s)	Average diameter of the jet tip (mm)	Depth of the cratering stage (mm)
1	56	RHA	5800	3.5	5
2	56	STEEL1006	5800	3.5	7
3	56	COPPER	5800	3	9
4	56	ALUMINUM	5800	3	7
5	82	RHA	5910	4.5	6
6	82	STEEL1006	5910	4	8
7	82	COPPER	5910	3.5	10
8	82	ALUMINUM	5910	4	10

Note: The stand-off of the shaped charge with the caliber of 82 mm is 164 mm and parameters of simulation modeling are shown in Literature [11], the same below.

Tab.2 The calculation conditions and results of charge LX-14

Example	Charge caliber (mm)	Target material	Jet tip velocity at the time of impact (m/s)	Average diameter of the jet tip (mm)	Depth of the cratering stage (mm)
1	56	RHA	7200	3.5	5
2	56	STEEL1006	7200	3	7
3	56	COPPER	7200	3	10
4	56	ALUMINUM	7200	3	8

5	82	RHA	8090	4.5	7
6	82	STEEL1006	8090	4.5	12
7	82	COPPER	8090	4	14
8	82	ALUMINUM	8090	4	12

It can be seen from Table 1 and Table 2 that, under the condition of the shaped charge structure and stand-off proposed in this Paper, : (1) with the same caliber, the jet impact velocity formed by LX-14 charge is higher than that of TNT, and the corresponding depth of the cratering stage is increased. The jet tip velocity at the time of impact formed by 56 mm charge increases by approximately 24.1% but the depth of the cratering stage does not distinctly increased; the jet tip velocity at the time of impact formed by 82 mm charge increases by approximately 36.9% and the depth of the depth of cratering stage averagely increases by about 31.7%. (2) With the same charge, the jet tip velocity and diameter at the time of impact increases as the charge caliber is increased, and the depth of the cratering stage also correspondingly rises. The diameter of the jet tip formed by 82 mm caliber charge averagely increases by about 1 mm compared with that of 56 mm caliber charge, with the jet tip velocity of TNT charge increasing by about 1.9% and the depth of the cratering stage increasing by about 22.1%; the jet tip velocity of LX-14 charge increases by about 12.4% and the depth of the cratering stage rises by about 50.4%. (3) With the same charge and caliber, the depth of the cratering stage of shaped charge jet in penetration into the target varies with different target materials, the depth of the cratering stage of COPPER target is maximum, and that of RHA target is minimum, indicating the influence of target intensity on the depth of the cratering stage is greater than the influence of target density. In short, the depths of cratering stage of shaped charge jet in penetration into targets are different under different working conditions, providing reliable data support for subsequent depth model fitting.

3. DEPTH MODEL

3.1. Building of the depth model

With respect to the empirical formula of the depth of cratering stage, the expression of the depth of the cratering stage of the projectile body in penetration into the target is obtained by way of fitting of dimensionless parameters of $v_P\big/\sqrt{R_t/\rho_t}$ and $\rho_p\big/\rho_t$ in [7,8] literatures:

$$\frac{p_c}{d_P}=a\cdot(\frac{\rho_P}{\rho_t})^b\cdot\left[\frac{v_P}{\sqrt{R_t/\rho_t}}\right]^c \qquad (1)$$

In the expression, p_c and d_P are respectively the depth of cratering stage and projectile diameter, v_p is the velocity of the penetrating body at the time of impact, *a*, *b*, and *c* are parameters, and when the projectile body penetrates into a thick target, $a=0.274$, $b=0.725$, and $c=2/3$. The formula applies to the condition that a high-speed projectile penetrates into a thick metal target. There is an error in the calculation of shaped charge jet penetrating into the target.

The cratering of the shaped charge jet's penetration is similar to the process in which projectile body penetrates into a thick target: near the impact point, the shock wave is strong, material pressure is high, and the function of the material compressibility is weaker than those of the quasi-steady penetration. Therefore, at the cratering stage in which the shaped charge jet penetrates into the target, the inertia and intensity effect are distinct, $v_P \big/ \sqrt{R_t / \rho_t}$ and $\rho_p \big/ \rho_t$ are still two important parameters of the stage, and the depth formula of the cratering of the shaped charge jet's penetration can be obtained with the use of fitting expression (1).

In combination with calculation results in Table 1 and Table 2, power function fitting is conducted on expression (1) with Matlab to get the depth formula of the cratering of shaped charge jet:

$$\frac{p_c}{d_j} = 0.215 \cdot \left(\frac{\rho_j}{\rho_t} \right)^{0.411} \cdot \left[\frac{v_j}{\sqrt{R_t / \rho_t}} \right]^{2/3} \quad (2)$$

In the formula, v_j and d_j are respectively the jet tip velocity and diameter at the time of impact. What shall be explained is that the target resistance, expressed by R_t, is related to the target intensity and density. Generally, when the jet velocity, expressed by V_j, is equal to the critical penetration velocity of the target, expressed by V_{jc}, the axial penetration velocity $u = 0$, $R_t = \frac{1}{2}\rho_j v_{jc}^2$. As a matter of fact, R_t is not a constant but a variable on V_j. The resistance of the target obtained from $R_t = \frac{1}{2}\rho_j v_{jc}^2$ is just an average value in the whole penetration process of shaped charge jet. Therefore, R_t of cratering stage of penetration is smaller than the actual value.

3.2. Simulation verification of the depth model

COMP B explosive is used as shaped charge, numerical simulation is conducted on the cratering stage of the shaped charge jet in penetration into targets, and simulation values and theoretical values are compared so as to verify the correctness of the theoretical model, with the result as shown in Table 3

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Tab.3 Comparison of simulation values and theoretical values of COMP B charge

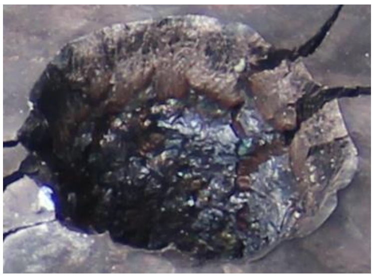
Example	Charge caliber (mm)	Target material	Jet tip velocity at the time of impact (m/s)	Average diameter of jet tip (mm)	Depth of cratering stage (mm)	Theoretical value （mm）	Error （%）
1	56	RHA	6520	3.5	5	4.8	4
2	56	STEEL1006	6520	3	7	6.7	4.3
3	56	COPPER	6520	3	9	9.5	5.6
4	56	ALUMINUM	6520	3	8	7.7	3.8
5	82	RHA	6915	4	6	5.7	5
6	82	STEEL1006	6915	3.5	8	8.1	1.3

7	82	COPPER	6915	3.5	11	11.6	5.5
8	82	ALUMINUM	6915	4	10	10.7	7

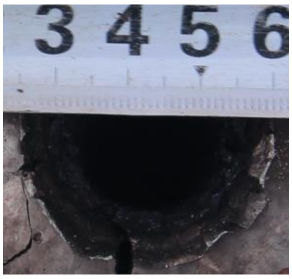
It can be seen from Table 3 that the jet tip velocity at the time of impact formed by COMP B charge is between that formed by TNT and that formed by LX-14, which indicates it is reliable to verify the depth formula with the use of model simulation value. On the depth of cratering stage, the average error between theoretical values and simulation values obtained from Formula (2) is 4.6%, and the maximum error is 7%, verifying the correctness of the depth model of the cratering stage.

3.3. Experimental verification of depth model

The penetration experiment corresponds to the simulation model as shown in Figure 1 and two experimental results are shown in Figure 4. The cratering stage is the initial stage of cratering of the shaped charge jet in penetration into the targets, the depth of cratering stage in experiment 1 is about 6.4 mm and that in experiment 2 is about 6.2 mm, the error between the theoretical value and average experimental value is 4.8%, and the depth of cratering stage is 2.1 times of jet diameter. It can be gained from the two experiments that the extreme penetration depth of experiment 1 is 225 mm and that of experiment 2 is 233 mm. The depth of cratering stage is 2.7% against the total penetration depth. The depths of the cratering stage of the two experiments coincide with the theoretical result, verifying the reliability of the theoretical model and numerical simulation.



a Cratering of the first target



b Cratering of the second target

Fig.4 The cratering results of targets

Experiment conditions are changed in order to further verify the correctness of the depth model of the cratering stage. Experiment parameters and overall arrangement are shown in Literature [14], and the experiment result is shown in Figure 5. The left of the figure shows the observation from the upward side of the cratering and the right shows the comparison of the profile of the penetration depth of shaped charge jet and the scale, with the minimum scale value of 1in=2.54 mm. It can be seen from the figure that the extreme penetration depth is about 1ft=25.4 mm and the initial cratering diameter is about 1.5in=3.8 mm. In the experiment, the distance between the virtually original point and the target is 25 mm, and the jet tip velocity arriving at the aluminum plate is about 5,000 m/s measured by two laser velocity measurement boards. The depth of cratering stage is 0.897 mm with the use of the depth formula of cratering stage, which is located at the white full line in Figure 5, approximately 4.5 times of jet diameter, accounting for 3.5% against the total penetration depth. This coincides with the experiment result in the figure.

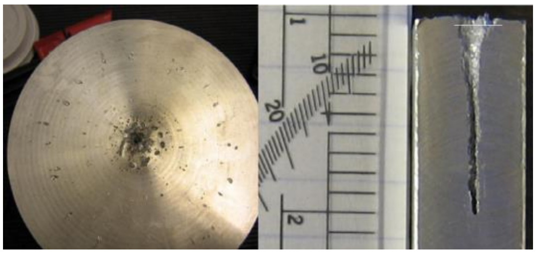


Fig.5 The comparison of depth of cratering stage and total penetration depth

3.4. Analysis of the depth model

The variation of the depths of cratering stage of shaped charge jets with different diameters as the jet tip velocity changes is shown in Figure 6. It can be seen from the Figure that as the jet tip velocity increases, the depth of cratering stage of penetration is greater and the depth of cratering stage tends to distinctly increases. When the jet tip velocity is improved from 4,500 m/s to 8,500 m/s, the depths of cratering stage of shaped charge jets with different diameters in penetration averagely increases by approximately 52.7%, in which the increase ratio of that of the shaped charge jet with 3 mm diameter is the greatest, about 53.8%, and the increase amplitude of that of shaped charge jet with 5 mm diameter is the largest, about 4.6 mm. This is because the depth of cratering stage of the shaped charge jet with 5 mm diameter is maximum, approximately 8.7 mm, when the jet tip velocity is about 4,500 m/s, and the increase ratio is about 52.9% even though the increase amplitude of the depth of cratering stage is the greatest. When the jet tip velocity of 6,000 m/s is randomly taken, the depth of cratering stage averagely increases by about 2.1 mm as the jet tip diameter increases by per 1 mm.

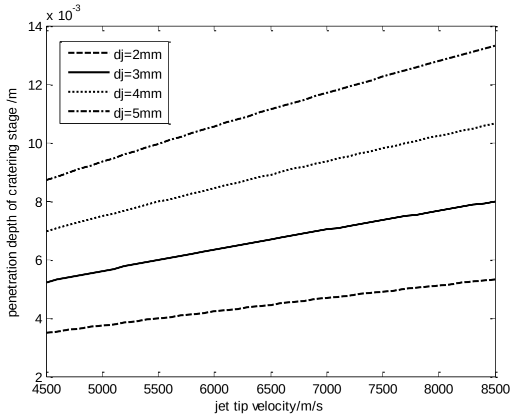
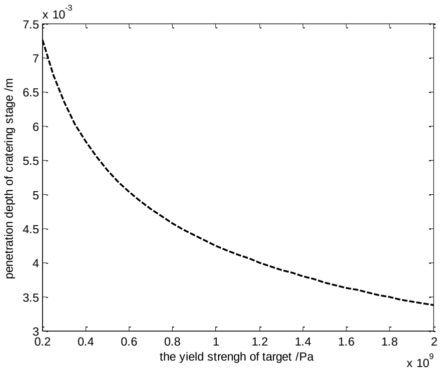
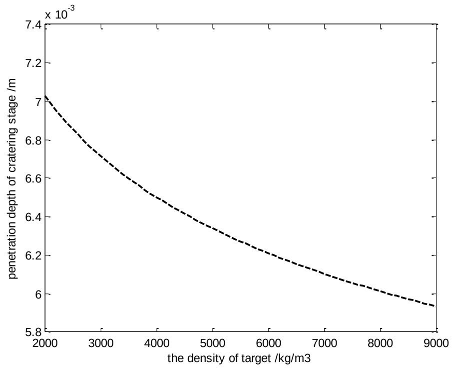


Fig.6 Variation of the depth of cratering stage of the shaped charge jet with different diameters as the jet tip velocity changes

Figure 7 shows the variation of the penetration depth of cratering stage with changes of the yield strength and density of target. It can be seen from (a) that the depth of the cratering stage presents logarithmic curve reduction with the increase of the yield strength. Before 800 MPa, the reduction trend is distinct, reducing by approximately 37%; after 800 MPa, the reduction of the depth of the cratering stage slows down with the increase of the yield strength. (b) shows the variation of the penetration depth of cratering stage with the change of the target density, in which the depth of the cratering stage reduces by about 1 mm when the density of the target increases from 2,000 kg/m^3 to 9,000 kg/m^3. (a) and (b) verify that the influence of the yield strength of the target on the penetration depth of the cratering stage is greater than that of the density of the target.



(a)



(b)

Fig.7 The variation of depth of cratering stage with changes of yield strength and density of target

4. CONCLUSIONS

The depth model of the cratering stage of the shaped charge jet in penetration into targets is gained in combination with numerical simulation, formula fitting, and experimental verification:

(1) The depth formula of the cratering stage of projectile penetrating into targets is amended and the depth model of cratering stage of penetration of shaped charge jet is obtained with the use of the simulation results of depths of cratering stages of various examples.

(2) Compared with simulation results under different working conditions, the average error between the theoretical values and simulated values of the depths of cratering stages is 4.6% and the maximum error is 7%. Compared with the experimental result, the errors between theoretical results and experimental results are within 5%, which verifies the correctness of the depth model of the cratering stage.

(3) It is known from analysis of the depth model that the depth of cratering stage distinctly increases with the increase of the jet tip velocity as the jet tip diameter is greater. The influence of the strength of a target on the penetration depth of the cratering stage is greater than that of the density of the target.

This has guiding significance for the study on the protective capacity of a multi-layer target and the penetration capacity of broken jets.

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