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Influence of Wave Shaper Position on Jet Formation and Penetration Depth

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Abstract:

The article presents the influence of the wave shaper position on the jet formation and penetration depth of a shaped charge, which uses the liner of the PG-7VM warhead by numerical method and experimental method. The results show that, when moving the plexiglass wave shaper position towards the liner apex, the jet tip velocity and the jet velocity gradient increase. In addition, the results of the study also pointed out the existence of the wave shaper position at which the penetration depth is greatest. They indicate a match between the simulation and experimental results. The differences between simulated and experimental penetration depth are less than 15%. The results of the study are the basis for the evaluation of the influence of the wave shaper position on the liner collapse and the reasonable use of the wave shaper in the structure of the shaped charge.

Keywords:

jet formation, jet velocity, penetration depth, shaped charge, wave shaper

1. Introduction

During the explosion process, it is possible to control the detonation wave to focus the energy of the charge that makes up the line, region, and surface where there are extremely high density and pressure. The phenomenon of explosion energy concentration is widely applied in both the military and civilian areas. In the military field, it may be encountered in the structure of a shaped charge and an explosively formed penetrator. One of the detonation wave control schemes to increase the penetration depth of the shaped charge is the use of a wave shaper in its structure. When using the wave shap-

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er, its position has an important influence on the penetration depth of the shaped charge. This conclusion has been presented in several documents. However, the quantitative research of the influence of the wave shaper position on the penetration depth of the shaped charge given in some documents was not fully evaluated [1-5].

Marina [1] proposed the method of calculating the penetration depth of the shaped charge taking into account the effect of the sub-initiation point (*T* point in Fig. 1). The calculated result of this method shows that the penetration depth increases when the wave shaper diameter is constant if the position of the sub-initiation point moves to the top of the liner. However, in practice, the wave shaper position is not placed at the top of the liner. It suggests that the wave shaper position at the top of the liner is not the optimal position.

Zhu et al. [2] researched the process of controlling the Mach wave surface in the structure of the shaped charge with the use of the wave shaper. Results indicate that when the wave shaper is embedded in charge, the pressure behind the Mach wave can be controlled by changing the wave shaper diameter and the distance between the wave shaper and the liner.

Zu et al. [3] investigated the detonation wave propagation in the shaped charge using the wave shaper. The calculated result indicates that the three types of detonation wave surfaces, such as conical detonation wave, spherical detonation wave, and flat explosive wave can be formed in the main charge by the change of the wave shaper thickness. At the same time, the flat wave surface is better than two other wave surfaces in increasing the length – diameter ratio of the explosively-formed projectiles and keeping the nose of the warhead intact.

Guo et al. [4] studied the effect of the wave shaper on jet parameters and penetration depth. The research results show that jet tip velocity, and jet velocity gradient increase if the wave shaper is used.

Hussain [5] and Guo et al. [4] asserted that the angle between the detonation wave surface and liner generatrix when using the wave shaper is smaller than in the case of not using the wave shaper. Therefore, the pressure after the wave surface impacting the liner increases when using the wave shaper.

The purpose of the article is to study the effect of the wave shaper position on the jet formation and penetration depth with the Ansys Autodyn 2D software. The process of the detonation wave propagation, jet parameters such as kinetic energy, the jet velocity gradient and jet tip velocity have been presented in this study. Besides, experiments were also conducted to determine the penetration depth of the shaped charge using the liner of the PG-7VM warhead with different positions of the wave shaper. The experimental results were analysed and compared with simulated results.

2. Numerical Method and Material Model

Based on [6, 7], the simulation problem consists of the process of forming the jet and the impact of the jet into the steel target. The jet parameters obtained in the simulation of the jet formation are the inputs for the simulation of the impact of the jet into the steel target. The material of the shaped charge components and the material models are given in Tab. 1.

The material parameters of the liner, the case, the para-charge, and the wave shaper are taken from the software library [8]. Material parameters of the main charge are presented in [9].

Tab. 1 Equation of state and material models

Part	Material	Equation of State	Strength Model	Failure Model
Liner	CU-OFHC	Shock	Steinberg-Guinan	–
Case	Polyethylene	Shock	–	–
Main charge	C4	Lee-Tarver	von Mises	–
Wave shaper	Plexiglass	Shock	–	–
Para-charge	C4	JWL	–	–
Target	C45 Steel	Shock	Johnson-Cook	Johnson-Cook

The shaped charge model used in the simulation is based on the structure of the PG-7VM warhead. This model is shown in the XOY coordinate system where OX is the symmetry axis of the shaped charge, T is the position of the sub-initiation point, *zws* is the distance between the wave shaper and the top O of the liner.

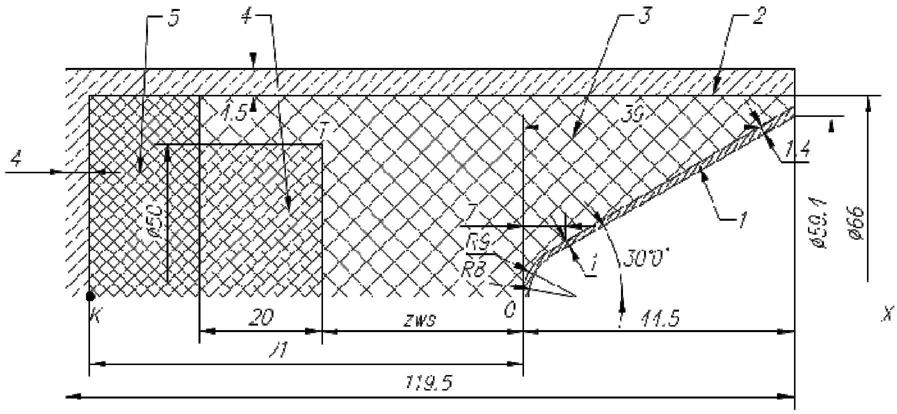


Fig. 1 The shaped charge model (in mm)

1 - Liner; 2 - Case; 3 - Main charge; 4 - Wave shaper; 5 - Para-charge; O - Origin of coordinates; T - Sub-initiation point; K - Detonation point.

The construction of simulation models on Ansys Autodyn 2D software is based on the geometric dimensions shown in Fig. 1. Due to the symmetry of the shaped charge, the multi-material Euler-2D solver is used to simulate the propagation of the detonation wave and the liner collapse [6, 7]. In the simulation model of the process of the jet formation, the size of the square cells was selected to be 0.25 mm. The interactions of detonation products and case at the boundary of the calculation area are not considered. The simulation time ends when the jet tip reaches a distance of twice the charge diameter from the liner base [6, 7]. This distance is fixed during the simulation to be able to evaluate the effects of the wave shaper position on the jet formation and penetration depth. It is not the optimal standoff distance for the maximum penetration depth. The point detonation method is used in the simulation. The position of the detonation point *K* is shown in Fig. 1. The Flowout boundary condition is applied to all computational boundaries. It allows the detonation products to expand and the case to fly out of the computation area without interacting with the boundaries and without affecting the collapse of the liner. The simulation model of shaped charge is shown in Fig. 2.

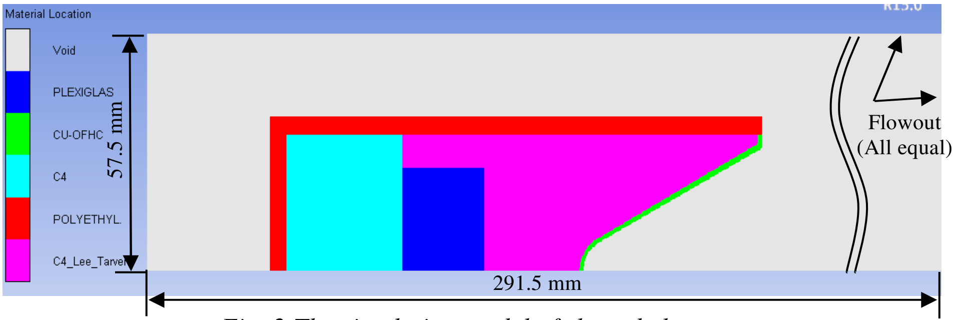


Fig. 2 The simulation model of shaped charge

In the penetration process simulation, the Lagrange grid is applied for both the jet and the target. The simulation results of the jet formation by the Euler method are used to determine the jet parameters. The jet strikes the target at a two-charge-diameter standoff distance [6, 7]. The target material is C45 steel and the cylindrical target is 130 mm in diameter and 400 mm in length. The equation of state for the target material is shock state equation, while its strength model and failure model are the Johnson-Cook constitutive model [10]. The simulation model of the impact process between the jet and the steel target is shown in Fig. 3. Both the jet and the target parts are modeled using 0.5 mm rectangular elements [6]. For the target, however, the mesh size is extended in the direction of the radius from the radius of 15 mm to reduce the total number of elements. Because of the symmetry, the simulation was performed with half of the models of both the jet and the target.

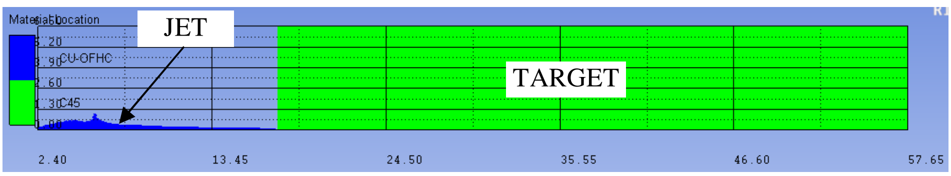


Fig.3 Simulation model of impact process between the jet and the steel target

The options are given in Tab. 2 with different positions of the wave shaper, which affect the simulation results.

Tab. 2. Different positions of wave shaper

Options	1	2	3	4
zws [mm]	–33	–23	–13	0

3. Experiment

To assess the results of the simulation method, the experiments with different wave shaper positions have been carried out. The shaped charge configurations used in the experiments are based on the simulation model in previous chapter.

3.1. Shaped Charge and Experimental Target

The liner used for experimental shaped charges is the liner of the PG-7VM warhead, whose dimensions are shown in Fig. 4.

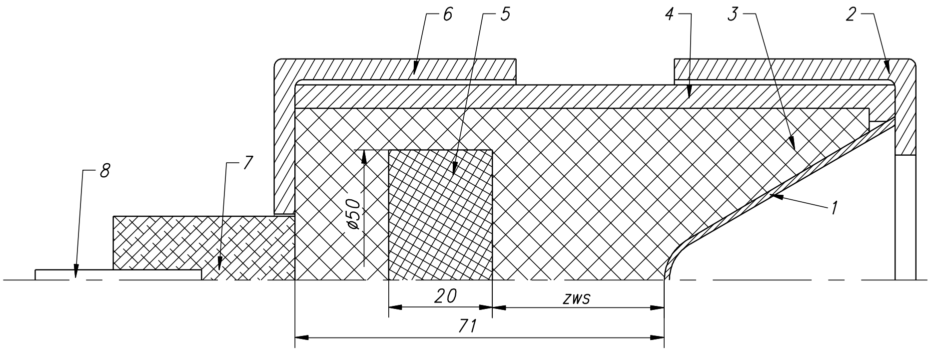


Fig. 4 Geometric model of experimental shaped charge [mm]

1 - Liner; 2 - Top cover; 3 - Explosive; 4 - Case; 5 - Wave shaper; 6 - Bottom cover; 7 - Booster; 8 - Detonator

The material of the liner is copper. The material of the covers and the case is PE. The material of the wave shaper is plexiglass. The dimensions of the cylindrical wave shaper are 50 mm in diameter and 20 mm in thickness (Fig. 5). The material of the booster is the TГ-50 explosive. The material of the explosive is composition C-4. The electrical detonator is used to detonate the booster. The material of target is C45 steel. The dimensions of the cylindrical target are 130 mm in diameter and 300 mm in length (Fig. 6).

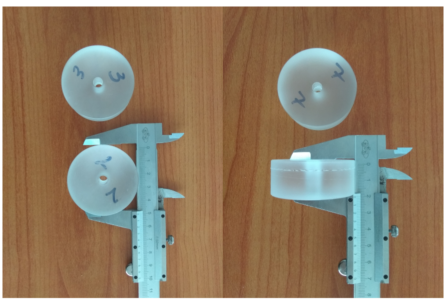


Fig. 5 Wave shaper

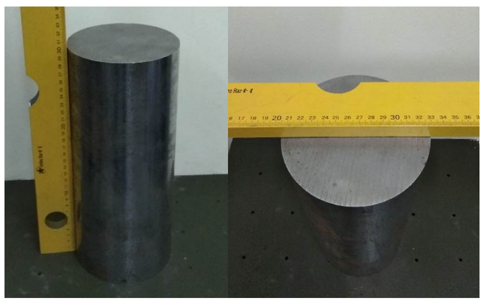


Fig. 6 Target

3.2. Experimental Setup

The experimental shaped charges whose model is in Fig. 4 after being filled with explosives and assembled are shown in Fig. 7. The experimental setup is shown in Fig. 8. The two-charge-diameter standoff distance is achieved by a plastic tube attached to the tip of the experimental shaped charge.

Fig. 7 Experimental shaped charges

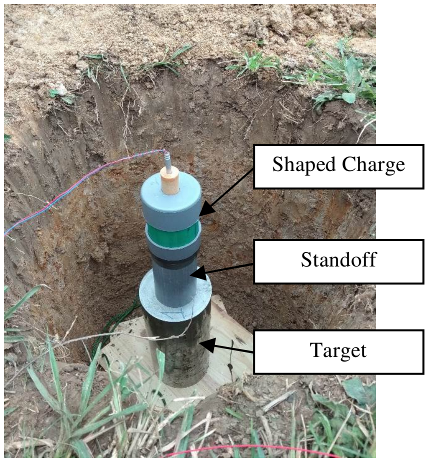
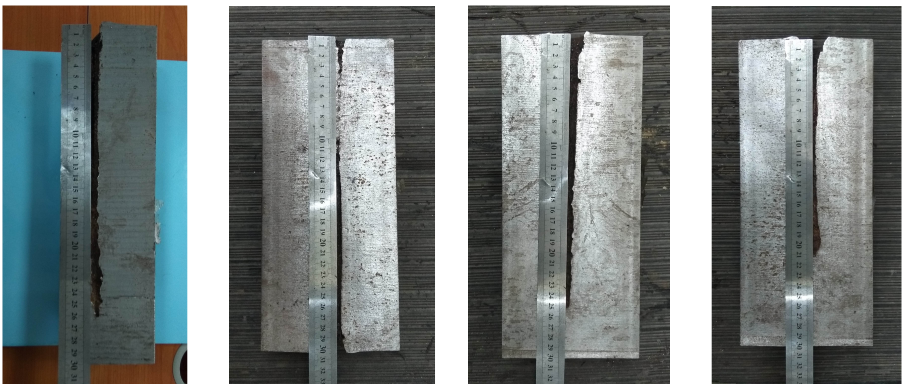


Fig. 8 Experimental setup

3.3. Test Results of the Influence of Wave Shaper Position on Penetration Depth

After the static explosion of the experimental samples, the steel targets were cut to determine the penetration depth (Fig. 9).



(a) *zws* = –33 mm (b) *zws* = –23 mm (c) *zws* = –13 mm (d) *zws* = 0 mm

Fig. 9 A number of steel targets cut at different positions of the wave shaper

Experimental penetration depth results for each wave shaper position are shown in Tab. 3.

4. Analysis and Discussion

In this chapter, analyses of detonation wave propagation behavior and jet tip velocity will be presented. These analyses can explain the tendency of changing of simulational penetration, which was compared with experimental penetration.

4.1. Detonation Wave Propagation Behavior

When the wave shaper is inserted in a shaped charge, it can change the direction of the detonation wave surface, which propagates in the charge. The detonation wave surface behind the wave shaper includes the interference of the wave surfaces. One part of the wave propagates around the wave shaper, and the rest passes through the wave shaper. If the angle between the detonation wave surface and liner generatrix is called β, the simulation results show that the angle β decreases as the wave shaper position approaches the top of the liner (Fig. 10). According to [4], when the angle β decreases, the detonation products behind the detonation wave surface will impact the liner at a higher speed, which increases the collapse velocity.

Tab. 3 Experimental penetration depth results

zws [mm]	Shot	Penetration depth [mm]	Average penetration depth [mm]
–33	1	286	274
	2	262	
	3	275	
–23	1	286	288
	2	277	
	3	300	
–13	1	279	269
	2	261	
	3	267	
0	1	209	219
	2	239	
	3	210	

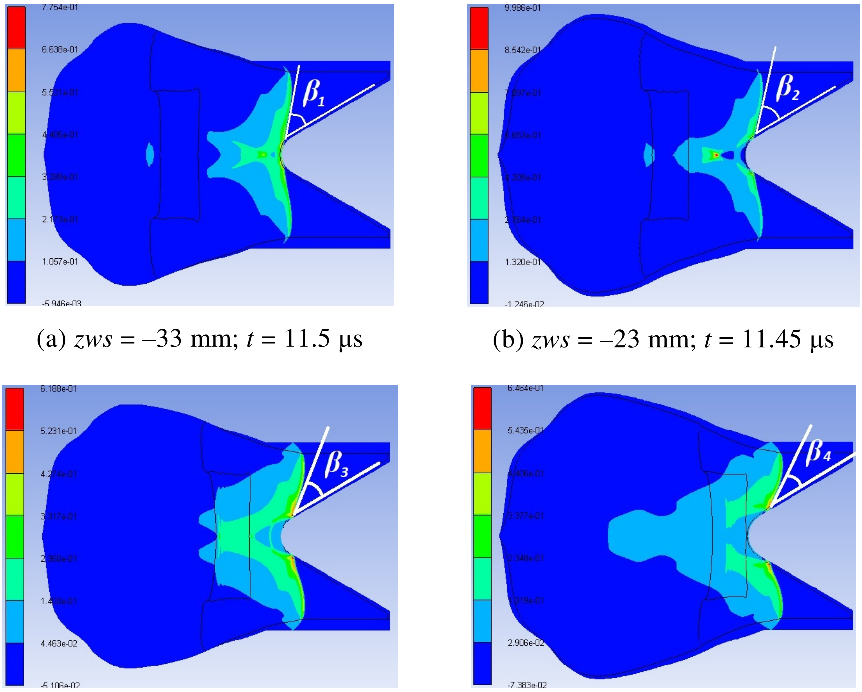
4.2. Jet Tip Velocity and Jet Velocity Gradient

When the wave shaper position is towards the top of the liner, the detonation wave surface changes in the direction of reducing the angle β. It causes an increase in the pressure of the wave surface. As a result, the collapse velocity increases. The liner elements that move towards the symmetry axis of the shaped charge form the jet tip with increasing tip velocity (Tab. 4). The jet tip velocity at $zws = 0$ mm increased by 18.1% compared to the one at $zws = -33$ mm. Also, the jet velocity gradient increases (Fig. 11). It is one of the factors that increase penetration depth.

The increase in the jet tip velocity and the jet velocity gradient causes the kinetic energy of the jet increase. However, as the wave shaper position moves closer to the top of the liner, the mass of the liner elements involved in the jet tip decrease. It is the reason for the reduction of jet kinetic energy despite the high jet tip velocity and jet velocity gradient. The jet kinetic energy at $zws = -33$ mm is 19.1% greater than the one at $zws = 0$ mm. The jet kinetic energy diagram according to the wave shaper position at a two-charge-diameter standoff distance is shown in Fig. 12.

4.3. Penetration Performance

The penetration depth results calculated by the simulation method (Fig. 13) show that, when the wave shaper position approaches the top of the liner, the penetration depth increases gradually and then decreases. The maximum value of penetration depth is 321 mm at the position $zws = -23$ mm.



(a) *zws* = –33 mm; *t* = 11.5 μs (b) *zws* = –23 mm; *t* = 11.45 μs

(c) *zws* = –13 mm; *t* = 11.4 μs (d) *zws* = 0 mm; *t* = 11.8 μs

Fig. 10 Propagation behavior of detonation wave in explosion process

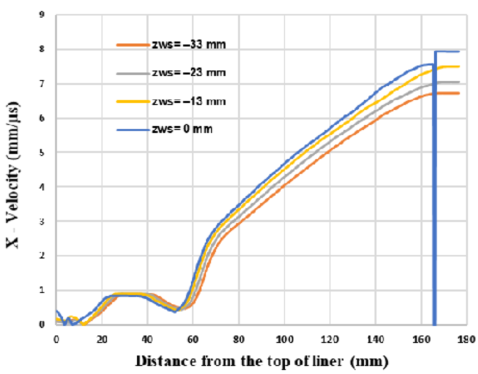


Fig. 11 Velocity gradient of jet along the symmetry axis of the shaped charge

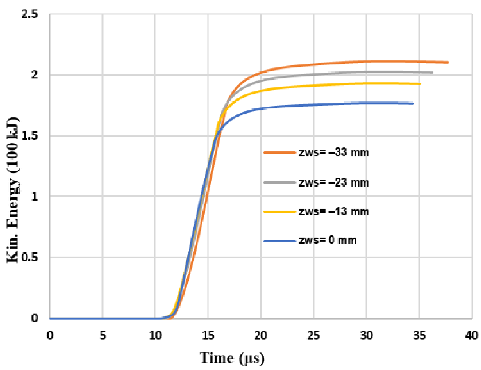


Fig. 12 Energy-time curves for different positions of the wave shaper

Tab. 4 Tip velocity according to different positions of the wave shaper at a two-charge-diameter standoff distance

zws [mm]	–33	–23	–13	0
Jet tip velocity [mm/μs]	6.719	7.048	7.505	7.935

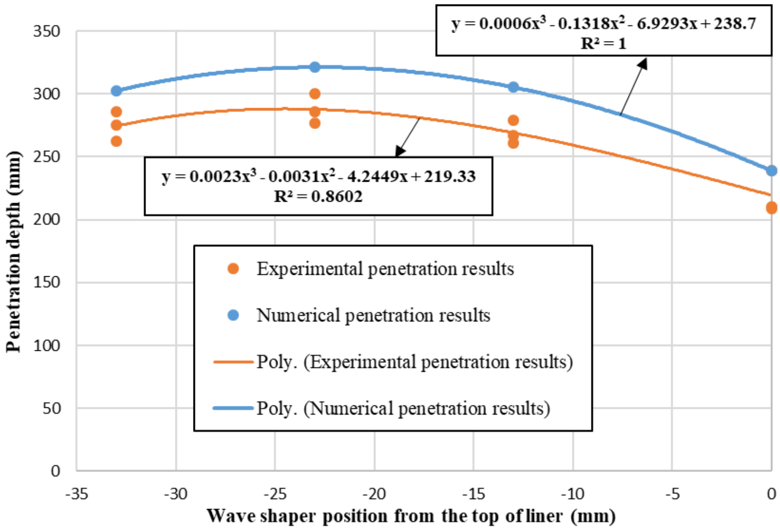


Fig. 13 Comparison of experimental and numerical penetration results

When *zws* increases from –33 mm to –23 mm, the penetration depth increases. The increasing trend of the penetration depth is because the closer the wave shaper position approaches the top of the liner, the more perpendicularly the wave surface is compressed to the liner surface, and the smaller the angle β is, respectively (Fig. 10). As a result, the jet tip velocity and jet velocity gradient increase. These factors are the cause of increasing penetration depth.

When *zws* continues to increase from –23 mm to 0 mm (at the top of the liner), the penetration depth tends to decrease. This is explained by two reasons: one is the decrease in jet tip mass and the other is the increase in velocity gradient (Fig. 11). These factors cause the kinetic energy to decrease (Fig. 12) and the jet to be broken during the penetration. Therefore, the penetration depth decreases as the wave shaper position is closer to the top of the liner.

The deviations between the simulation and the experimental average results of the penetration depth with *zws* = –33 mm, *zws* = –23 mm, *zws* = –13 mm and *zws* = 0 mm are 10.2%, 11.6%, 13.5% and 8.8%, respectively. These results show the validity of the simulation method when the wave shaper position changes. The deviation between simulation and experiment is less than 15% within the permitted range.

5. Conclusion

The influence of the wave shaper position on the jet formation and the penetration depth to the steel target is presented in this study. The following conclusions have been drawn:

- when the wave shaper position approaches the top of the liner, the detonation wave surface changes in the direction of reducing the angle between the detonation wave surface and liner generatrix. This effect increases the pressure of the wave surface and causes an increase in jet tip velocity and velocity gradient,

- when the wave shaper position is closer to the top of the liner, there is a value of the wave shaper position at which the penetration depth is maximized,
- the simulation method presented in this study allows assessing the influence of wave shaper position on the jet parameters and the penetration depth. The experimental results show the validity of the simulation method. The difference between the penetration depth of simulation and the experiment is less than 15%.

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