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Demolition Mechanism and Behavior of Shaped Charge with Reactive Liner

Jianguang Xiao,[a] Xuepeng Zhang,[a] Yongzhi Wang,[a] Fengyue Xu,[a] and Haifu Wang*[a]

Abstract: The application of reactive materials on shaped charge liners has received much attention. Herein, the demolition mechanism and behavior of reactive materials based shaped charge liner are investigated by experiment, numerical simulation, and theoretical analysis. Three reactive shaped charge liners, composed of a mixture of Al/PTFE (26.5/73.5 wt-%) powders, are fabricated by pressing and sintering. The damage effects of the multi-layered target against reactive materials based shaped charge are investigated. The results show that the reactive liners create excellent collateral damage due to the release of chemical energy contained in reactive materials. An Eulerian computational model is developed to investigate penetration behavior of the reactive jet formed by shaped charge liner. In addition, a theoretical model based on cavity expansion is derived to predict the initiated location of reactive materials. Comprehensive analysis indicates that the TNT equivalence factor for these powder mixtures used in this work is 3.41–7.77 and that the self-delay time is about 0.8 ms. This work will provide guidance and reference for the design of reactive shaped charge liner.

Keywords: Reactive materials · Shaped charge liner · Demolition mechanism · TNT equivalence · Self-delay time

1 Introduction

Reactive materials are a class of solid energetic materials that are formulated to release energy under highly dynamic loads. In general, they are formed by introducing active metal powders into a polymer binder, typically such as PTFE, and then consolidated by a press/sinter process. Remarkably different from traditional energetic materials, they have features of high mechanical strength and sufficient insensitivity so as not to sustain a deflagration reaction using traditional initiation techniques, such as exploding bridge wires or flame initiation [1,2]. As such, the mechanical work of a high-strain-rate plastic deformation process is required to provide the necessary energy to drive the reaction.

Due to their unique performance, reactive materials have a great variety of applications, and have been intensively investigated in the past decade [3–9]. One of the most important applications is demolition. Several researches show that much greater efficiency could be achieved by reactive materials based shaped charge liner (reactive liner), which could release chemical energy in the target. The lethality of reactive liner against concrete targets was demonstrated by E. L. Baker [10,11]. Reactive jets were identified and they were found to create much more collateral damage than inert ones, as a result of the chemical energy released inside the targets during or after the penetration process. Although the excellent damage effects were confirmed, the demolition mechanism and behavior of this reactive material liner have not been understood well.

Although numerical simulation is a useful way to reappear the penetration and blast process of reactive jets, it is difficult to find an adequate constitutive modeling for reactive materials. For unreacted equation of state (EOS), Instron compression tests and high-rate split Hopkinson bar experiments were carried out to determine parameters of the Johnson-Cook model [12]. On the other hand, a theoretical model was developed to describe the blast characteristics, and a fitting method was employed to determine the corresponding parameters of reacted EOS [13].

The demolition behavior depending on penetration and blast effects of a reactive jet, is significantly influenced by the self-delay initiation time and chemical energy release of reactive materials. The total time of activation and self-delay that occurs in impact-initiated reactive materials is strongly dependent on the dynamic loads [1]. One step further, a higher stress value likely leads to a relatively shorter self-delay time. However, significantly different from an impact, when explosively activated, the stress imposed upon the reactive materials is much higher, and whether the higher stress will reduce the self-delay time remains unknown.

[a] J. Xiao, X. Zhang, Y. Wang, F. Xu, H. Wang
State Key Laboratory of Explosion Science and Technology
Beijing Institute of Technology
Beijing 100081, P. R. China
*e-mail: wanghf@bit.edu.cn

This paper begins with a description about the demolition mechanism and behavior of reactive materials based shaped charge, then the demolition effects are confirmed experimentally. At last, the self-delay time and TNT equivalence factor for reactive materials are discussed by theoretical analysis and numerical simulation.

2 Phenomenological Description Of Demolition Behavior

The typical configuration of a reactive shaped charge including detonator, main charge, and reactive liner is presented in Figure 1. The terminal demolition process can be

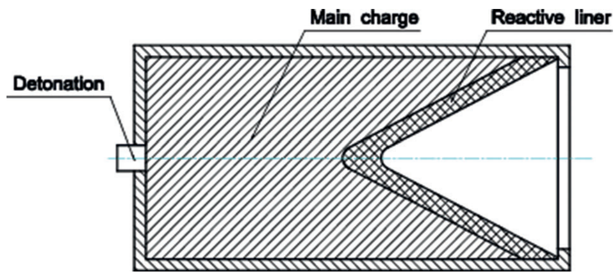

Figure 1. Configuration of the reactive liner shaped charge.

viewed as a three-stage event: (1) the formation of jet; (2) the penetration of inert-like jet; (3) the release of chemical energy contained in reactive materials. In order to have a better understanding of this demolition behavior, numerical simulation is used to have a closer look at the demolition process.

The pressure, generated by the detonation of the main charge, is of the order of 30 GPa. This extremely high pressure not only compresses the reactive liner to be a reactive penetrator, but also activates the reactive materials. As showed in Figure 2, the detonation wave travels in the main charge as well as the reactive liner. At the beginning of compressing liner, the only area, which is affected, is the cone top and the major part of reactive liner is still stress free. The required time for the detonation wave propagating from the cone top to the bottom of liner is 18 μs in the

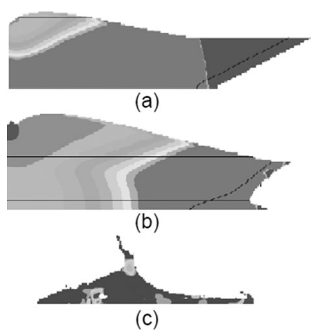

Figure 2. Formation of the jet.

current conditions. As time progresses, a reactive jet will be formed, as illustrated in Figure 2c. However, as a result of self-delay time, chemical reaction in the penetrator (jet) does not occur immediately after the activation.

Figure 3 presents the following important penetration process of the jet. During the penetration process, the length of jet increases persistently because of the gradient

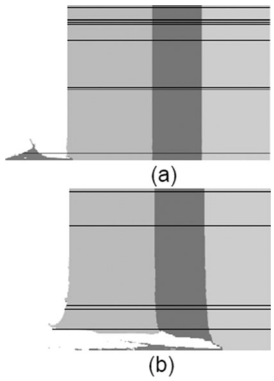

Figure 3. Penetration of the inert-like jet.

of velocity in the reactive materials: the head of the jet has a much higher speed than the tail. In fact, the penetration process won't cease until chemical reaction occurs in the penetrator, because, after chemical reaction, the solid-state reactive materials will change to gaseous-state that contributes scarcely penetration depth.

At the end of demolition process, detonation or deflagration may occur in the penetrator. The pressure wave produced will propagate in multi-layered targets; consequently, the mediums are crushed or fractured. Besides, the dilatation of detonation products does further damage to the target. At last, a standard demolition crater (Figure 4a) or a demolition cavity (Figure 4b) will appear, depending on both of the chemical energy released and initiation location of the penetrator in the process.

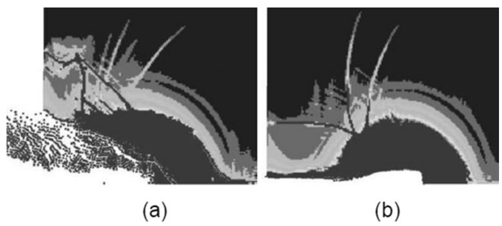

Figure 4. Release of chemical energy contained in reactive materials.

3 Experiments

3.1 Experimental Setup

The reactive shaped charge liners used in this study were composed of Al (26.5 wt-%) and Teflon (73.5 wt-%) powders.

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After being mixed, these powders were poured into a press die, where they experienced a pressure of 300 MPa in 10 min. Afterwards they were consolidated via sintering process. The ultimate reactive liner and reactive materials based shaped charge sample are shown in Figure 5. The main charge is composed of Composition B (60RDX/40TNT). The configuration of multi-layered target (3.6 m × 3.6 m × 0.6 m), including layers of concrete, gravel and soil, is shown in Figure 6. The unconfined compressive strength of concrete layer detected before experiments was 35 MPa.

In the experiments, three reactive materials-based shaped charges were fabricated and tested against the targets at one charge diameter stand-offs. The parameters of the shaped charges and damage effects are listed in Table 1.

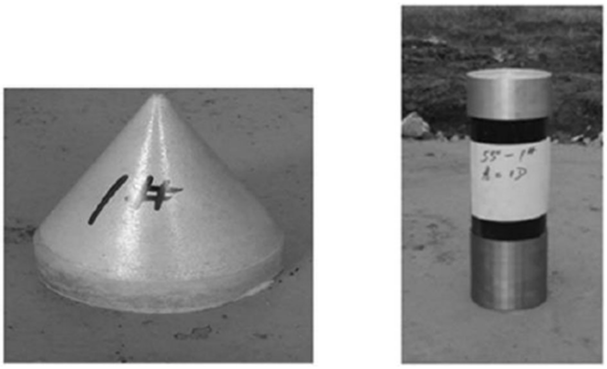

Figure 5. Reactive liner and shaped charge samples.

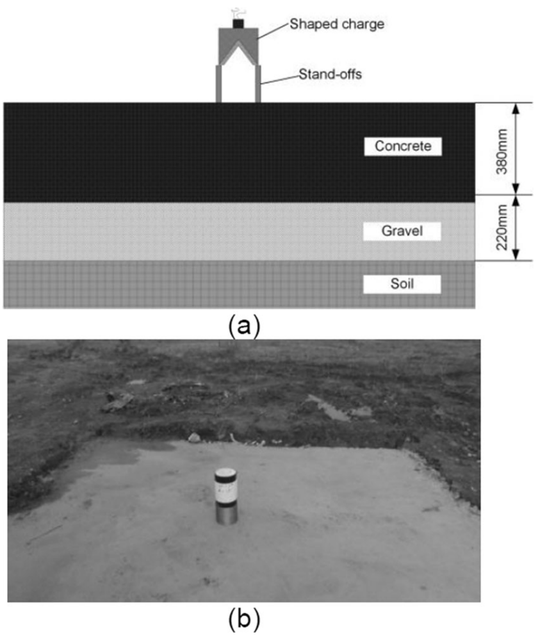

Figure 6. Schematic of the experimental setup.

3.2 Experimental Results

All of the reactive shaped charges, labeled A, B, and C, exhibit excellent damage effects, as illustrated in Figure 7. A standard demolition crater, which is similar to the case of a casting blast, is formed in experiment A. On the other hand, a demolition cavity, several cracks and deflections

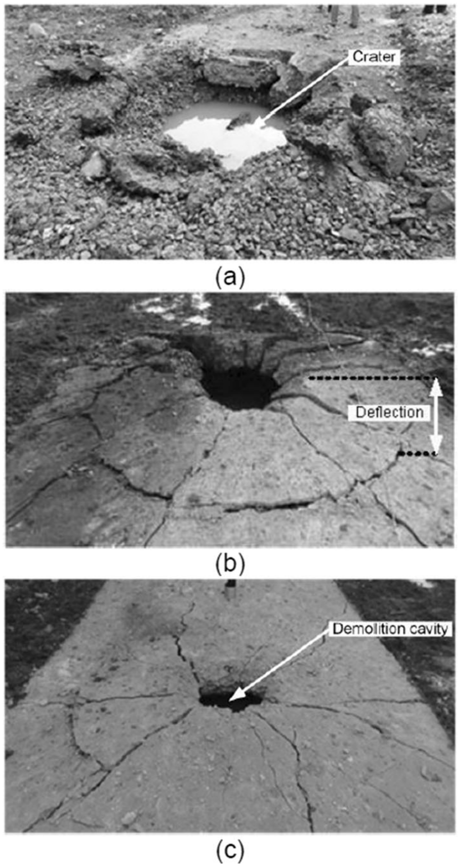

Figure 7. Damage effects of multi-layered concrete targets by different reactive liner shaped charge.

Table 1. Parameters of reactive materials based shaped charges and damage effects.

Sequence	Liner			Damage effects		
	Cone angle [°]	Diameter [mm]	Mass [g]	Crater depth [mm]	Damage diameter [mm]	Deflections [mm]
A	55	136.14	1295.2	830	3266 × 3500	120
B	65	137.98	1096.4	740	3300 × 4100	230
C	55	137.31	867.4	750	3100 × 3100	110

that is similar to the case of loosing blast, are observed in B and C. These cracks and deflections are more preferable than a standard demolition crater as they are likely more complex to be repaired. In conclusion, the damage model for A, B, and C is significantly different.

From Figure 7 it can be seen that the more reactive materials contained in a shaped charge liner, the more damage effects could be achieved. In fact, both of the mass of reactive materials and the initiation location have led to the differences of damage models. In other words, under given conditions of shaped charges and targets, there is an optimal initiation location for reactive materials to reach the appreciable damage effects.

The initiation location, which is dependent on the whole penetration process of the inert-like jet, may be highly dominated by the self-delay time: when the self-delay time doesn't exist, chemical reaction occurs immediately after the explosive activation, and even the jet is impossible to form so that the penetration depth will be zero; when the self-delay time is shorter than the whole penetration time related to a corresponding inert jet, the penetration depth increases as the self-delay time increases; when the self-delay time is sufficiently long, the penetration depth would reach the peak value, and the effects of the self-delay time disappear.

4 Discussion

4.1 Penetration Behavior

Numerical simulation of penetration process for the reactive jet was performed to address the penetration performance of the jets over time. Thus an Eulerian computation model was developed based on the platform of AUTODYN code. The shock equation of state and Johnson-Cook strength model were employed for reactive liner materials. The equation parameters were same to that calibrated by M. N. Raftenberg [12]. A relatively low value of the minimum density factor for material cutoffs was used to prevent cells from being over emptied.

The penetration depth and length of jets vs. time is shown in Figure 8. The initial-time is correspondent with the time when all of reactive materials were activated. As can be seen from the picture, the characteristics of penetration depth over time for the three reactive jets are approximate, whereas the length is remarkably different. The length of jet in experiment A is similar to that in C but is always larger than that in B. If the center of jet is regarded as the initiation location of the penetrator, one can infer that the initiation location in experiment B is always deeper than that in A and C.

Taking account of numerical simulation, the differences of demolition model in experiments could be well interpreted. The damage effects created in experiment B are less than that in A because of less reactive materials and deeper initiation location. Though the initiation location in A and C are approximate, it is the amount of reactive materials that leads to the different damage model.

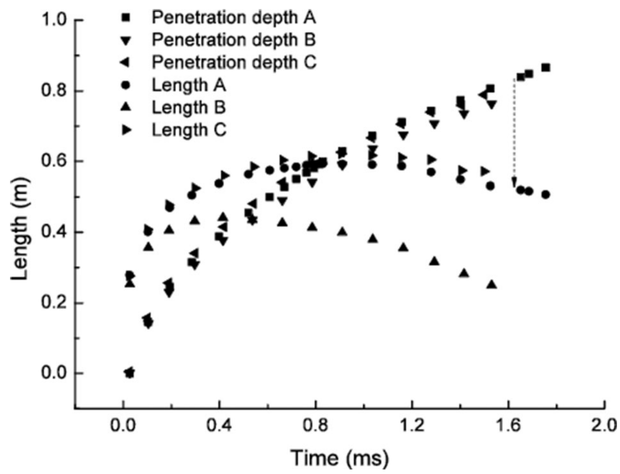

Figure 8. Penetration depth and length of jets.

4.2 Chemical Energy Release

After penetration, the multi-layered targets will be destroyed by the blast effects of reactive jet. In fact, it is deflagration or combustion that dominates the blast behavior. Compared with detonation, the pressures produced by the blast have features of lower intensity (of the order of 10^8 Pa) but longer temporal extent (of the order of a ms). However, the pressure impulse ($p \times t$) is likely of the same order. The relatively low pressure brings much difficulty to create collateral damage against high strength target, such as steel target, because the yield strength of steel is likely higher than the blast pressure. For concrete target, the yield strength is much weaker than the blast pressure so that the concrete will be destroyed.

For engineering purposes, the blast effects can be estimated with the aid of TNT equivalence. In this section, the TNT equivalence method is used to quantify the lethality capacity of reactive materials. The damage produced in experiment B and C is similar to the case of loosing blast (Figure 9a). The radius of the demolition cavity in an infinite target can be estimated by the following formula [14]:

$$r_y = K_y \sqrt[3]{w} \tag{1}$$

where r_y is the radius of the demolition cavity, K_y is constant, the value for concrete, gravel and soil is 0.19, 0.45, and 0.5, respectively, and w is the mass of TNT explosive.

From Equation (1) it can be concluded that r_y is proportional to K_y. Therefore, it is reasonable to define an equivalent radius of the demolition cavity in concrete as follows:

$$r_{ye} = \frac{1}{2}\left(L_c + \frac{K_{yc}}{K_{yg}} L_g + \frac{K_{yc}}{K_{ys}} L_s + \delta\right) \tag{2}$$

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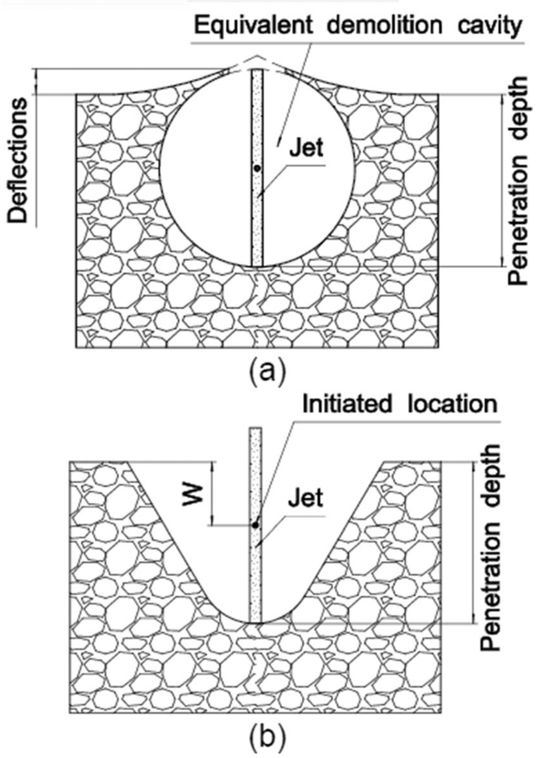

Figure 9. Sectional view of equivalent crater.

where δ is the deflections, L_c, L_g and L_s represent the damage length in concrete, gravel and soil layer of a multi-layered target, K_{yc}, K_{yg}, and K_{ys} are corresponding crushed zone coefficient.

Substituting Equation (2) to Equation (1), we can get the TNT equivalent weight for reactive materials (w) contained in experiment B and C.

In experiment A, a standard demolition crater, which could also be produced by casting blast, is observed (Figure 9b). Under such condition an experiential formula based on abundant experiments is used to describe the required TNT charge:

$$w = kW^3(0.4 + 0.6n^3) \tag{3}$$

where w is mass of TNT charge, $n = R/W$, R is radius of the damage area and W represents the initiated location of explosive, k is coefficient, and the value for concrete is 1.52.

When the initiated location is assumed to locate at the center of the jet, then it could be determined in the following when taking account of Figure 9b:

$$W = L_c + \frac{K_{yc}}{K_{yg}} L_g + \frac{K_{yc}}{K_{ys}} L_s - \frac{1}{2} L_{jet} \tag{4}$$

with L_{jet} as the length of the jet.

Substituting Equation (4) to Equation (3), one can get the TNT equivalent weight for reactive materials (w) contained in experiment A.

In the above mentioned equations, the only unknown parameter is L_{jet}. However, we have got penetration depth in experiment A. On the other hand, the penetration depth and length of jet (L_{jet}) vs. time could be obtained numerically, as showed in Figure 8. Along with the direction of the arrow, one can obtain the corresponding value of L_{jet}.

Ultimately, the TNT equivalence factor for reactive materials of unit mass is:

$$t = \frac{w}{m} \tag{5}$$

where m is the mass of reactive materials.

As listed in Table 2, the TNT equivalence factor for reactive materials calculated by Equation (5) is 3.41, 7.77, and 5.51, respectively. However, theoretical energy contained in Al/PTFE (26.5/73.5 wt-%) is just 14151 $\mathrm{J\,g^{-1}}$ (about four times of TNT). The relatively larger value estimated in this paper could be caused by neglecting the kinetic energy contained in the shaped charge jet, which also does much damage to these targets. When the average velocity of a 1 kg jet varies from 2000 to 6000 $\mathrm{m\,s^{-1}}$, the kinetic energy could reach 0.6–5.4 times TNT equivalence. The total of kinetic and chemical energy tends to be consistent with theoretical calculation results.

Table 2. The TNT equivalence factor and self-delay time.

Sequence	TNT equivalence factor	Self-delay [ms]
A	3.41	0.82
B	7.77	0.88
C	5.51	0.84

4.3 Self-Delay Time

Using the theory described above, the real initiation location of the inert-like jet can be estimated combining with experimental results. Moreover, the relationship between penetration depth and time could be obtained by numerical simulation. As such, the time corresponded to the real initiation location, which could be regarded as the self-delay time, is determined approximately.

Experimental researches show that the total initiation time including activation and self-delay of reactive materials is tens of microseconds [1]. However, the self-delay time of reactive materials estimated here is about 0.82–0.88 ms, which is longer than that of impact-initiated reactive materials. This analysis shows that the self-delay time hasn't been remarkably reduced under the higher stress. In fact, the stress states of reactive materials are fairly complicated.

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Though the stress imposed on the reactive liner is extremely high, the duration time showed by numerical simulation is very short yet, resulting in the longer self-delay time.

5 Conclusions

The demolition mechanism and behavior of reactive material liner shaped charge are researched. The main contributions of this paper are as follows:

(a) The demolition process of reactive material liner shaped charge consists of three phases: (1) the formation of jet; (2) the penetration of inert-like jet; (3) the release of chemical energy.
(b) The demolition effects of reactive material liner shaped charge are remarkably influenced by the initiation location and the mass of reactive material jet. For a given shaped charge, a proper initiation location is very important to produce a dramatically demolition crater, cracks and deflections.
(c) The reactive liner shaped charge is an extremely efficient demolition technology that incorporates the defeat mechanisms of a multi-stage shaped charge into a single one. The lethality capacity of reactive material liner against multi-layered concrete targets could reach about 3.41–7.77 times that of TNT.

Acknowledgments

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References

[1] R. G. Ames, *Energy Release Characteristics of Impact-Initiated Energetic Materials*, MRS Proceedings, Cambridge University Press, Cambridge, **2005**, p. 896.
[2] H. Wang, Y. Zheng, Q. Yu, Z. Liu, W. Yu, Impact-Induced Initiation and Energy Release Behavior of Reactive Materials, *J. Appl. Phys.* **2011**, *110*, 074904.
[3] D. B. Nielson, R. L. Tanner, G. K. Lund, *High Strength Reactive Materials and Methods of Making*, U.S. Patent 7307117B2, **2007**.
[4] E. L. Dreizin, Metal-Based Reactive Nanomaterials, *Prog. Energy Combust. Sci.* **2009**, *35*, 141 – 167.
[5] M. A. Zamkov, , R. W. Conner, D. D. Dlott, Ultrafast Chemistry of Nanoenergetic Materials Studied by Time-Resolved Infrared Spectroscopy: Aluminum Nanoparticles in Teflon, *J. Phys. Chem. C* **2007**, *111*, 10278–10284.
[6] E. M. Hunt, S. Malcolm, M. L. Pantoya, F. Davis, Impact Ignition of Nano and Micron Composite Energetic Materials, *Int. J. Impact Eng.* **2009**, *36*, 842 – 846.
[7] A. A. Denisaev, A. S. Shteinberg, A. A. Berlin, Initiation of a Reaction in Aluminum-Teflon Multilayer Thin-Film Samples by Drop-Hammer Impact Loading, *Russ. J. Phys. Chem. B* **2008**, *2*, 491 – 497.
[8] T. J. Blachowski, J. Burchett, US Navy Characterization of Two New Energetic Materials, CP and BNCP, *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Indianapolis, IN, USA; July 8–10, **2002**, AAIA paper 2002–3553.
[9] R. G. Ames, Vented Chamber Calorimetry for Impact-Initiated Energetic Materials, *43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, January 10–13, **2005**, p. 279.
[10] A. Daniels, E. Baker, K. Ng, A Unitary Demolition Warhead, *US Army, Picatinny Arsenal, Mines, Demolition and Non-Lethal Weapons Conference*, New Orleans, LA, USA, **2003**.
[11] A. S. Daniels, Bam Bam: Large Scale Unitary Demolition Warheads, *Proceedings of the 23rd International Symposium on Ballistics*, Tarragona, Spain, **2007**.
[12] M. N. Raftenberg, W. Mock, G. C. Kirby, Modeling the Impact Deformation of Rods of a Pressed PTFE/Al Composite Mixture, *Int. J. Impact Eng.* **2008**, *35*, 1735 – 1744.
[13] J.-W. Jiang, Modeling and Simulation of JWL Equation of State for Reactive Al/PTFE Mixture, *J. Beijing Inst. Technol. (Engl. Ed.)* **2012**, *21*, 150 – 156.
[14] The Eighth Department Writing Group of Beijing Institute of Technology, *Explosion and its Effects*, National Defence Industry Press, Beijing, **1979**.

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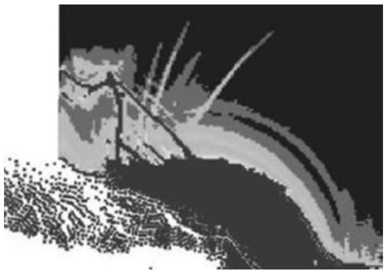

J. Xiao, X. Zhang, Y. Wang, F. Xu, H. Wang*

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