Observation of Debris Clouds Generated by Hypervelocity Impact of Copper Jets with Thin Aluminum Plats

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Abstract. With high kinetic energy and excellent penetration performance, metal jets have been widely used in the defence industry. When a thin plate is impacted by a metal jet with a velocity higher than 3 km/s, debris clouds will be generated at both sides of the plates. However, compared with the debris clouds generated by hypervelocity impact of projectiles, debris clouds generated by hypervelocity jets is rarely observed. In this paper, the utility of ultrahigh-speed simultaneous framing and streak photography technology is applied in the experiment of copper jets impact thin aluminum plates at hypervelocity. Debris clouds and front edges of shock waves are clearly observed and recognized after using newly developed technology to effectively restrain excessive exposure caused by intensive self-illumination in the experiment. From framing and streak pictures, the process of jets impact targets is comprehensively and completely recorded and the velocities of the jet and the debris cloud are obtained using the methods of data processing developed in present paper.

1. Introduction
For the need of protection against meteoroid/orbital debris, debris clouds generated by hypervelocity impact projectiles with thin plates have been observed and widely analyzed [1-4]. Based on images of debris cloud obtained by flash X-ray photography, high-speed photography or laser shadowgraph [5, 6], geometry structure and formation (failure evolution) of debris cloud are analyzed [7-9]. The X-ray photographs of debris clouds obtained by Piekutowski [1] have become the foundation of flowing theoretical and numerical research. However, detail information during the hypervelocity impact process, such as velocity of projectiles and shock waves, can hardly be obtained via X-ray photography.

The kinetic energy of projectiles is limited by loading equipment. Based on the two-stage gas gun, several grams of projectiles can be accelerated up to 10 km/s. Compared to projectiles, metal jets with higher velocities have better penetration performance. When a thin plate is impacted by a metal jet with a velocity higher than 3 km/s, debris clouds will be generated at both sides of the plates. However, debris clouds generated by hypervelocity jets have rarely been observed and analyzed [10].

In this paper, debris clouds generated by hypervelocity impact of copper jets with thin aluminum plates are observed based on ultrahigh-speed photography technology and simultaneous framing and streak camera.

2. Experimental method
To analyze the phenomenon of debris clouds generated by hypervelocity impact jets with thin plates, an experimental system of hypervelocity jets impact thin plates is designed. As shown in Fig. 1(a), the system consists of a jet launcher, a target plate, a reflective mirror, the simultaneous framing and streak camera, the laser illumination system and the protective equipment. Because experiments in
present paper are conducted in a blasting tower, the protective equipment include the wall of the tower and the window glass on it. The jet launcher consists of a shape charge cover, the main explosive and the primary explosive, as shown in Fig. 1(b). The principle and the technology of the simultaneous framing and streak camera and the laser illumination system will be introduced in next section.

In the jet launcher of our experiments, the 50 mm standard jet source (main explosive: J0-8 explosive, shape charge cover: copper) is used. The main explosive is detonated by a JH14 explosive (10 mm in length and 10 mm in diameter) at its central. To analyze the influence of the target thickness, LY12 aluminum targets with 2 mm and 4 mm in thickness are used.

Before the experiments are conducted, simultaneous framing and streak camera and the laser illumination system should be set. The reflective mirror is adjusted to make sure the laser light path through the window on the wall of the blasting tower and enter the center of the view of the camera. To ensure the imaging quality, K9 glass is used for the window on the wall of the blasting tower and the reflectivity of the reflective mirror should be higher than 90%. Position and attitude of the jet launcher are determined by a level bar and a laser leveler. The jet should vertically impact the horizontal target plate. The impact area should be located in the view of the camera, and the medial axis of the jet should coincide with the symmetric line of the view.

When the experiments are conducted, the laser illumination system starts up by an impulse signal generated by the delay initiator. The detonation probe made by a thin copper wine is convolved on the main explosive and connects to the camera and the oscilloscope via the trigger line. The shutter of the camera is opened when the trigger signal caused by detonation probe meets the setting value.

![Figure 1](image)

(a) Top view of the experimental system
(b) Front view of jets impacting targets

**Figure 1.** Schematic diagram of experimental system of jets impacting targets

Because the exposure time of the simultaneous framing and streak camera is relatively short, the duration time of the transient event measured should be precisely estimated to ensure the transient process concerned be completely recorded by the camera. In present experiments, the time difference from the jet enters the view to the detonation wave arrives the trigger probe, $\Delta T$ calculated from the following equation, is taken as the reference of the time delay setting of the camera.

$$\Delta T = \frac{H_1 + H_2 - H_3}{V_j}$$  \(1\)

in which $H_1$ is the distance from the trigger probe to the bottom of the shape charge cover, $H_2$ is the distance from the bottom of the shape charge cover to the top of the target plate, $H_3$ is the distance
from the top of the target plate to the bottom of the view of the camera. The velocity of the jet (standard jet source) \( V_j = 8.4 \text{ km/s} \).

3. Ultrahigh-speed simultaneous framing and streak photography technology

3.1. Simultaneous framing and streak camera

The simultaneous framing and streak camera can simultaneously take ultrahigh-speed framing photograph and streak photograph in a single experiment. Therefore, the photographs of the transient event at the same time base, same space base are obtained, as well as the information of the optical power, 1D time and 2D spatial information. The experimental data obtained from the camera is far more than that individually obtained from the framing photography system or the streak photography system. Comparing the 2D spatial information at the sample points of the framing photograph with the continuous record of the whole process from the streak photograph, more detail of the transient event is obtained and advantages of the framing photography and the streak photography is complemented.

The simultaneous framing and streak camera used in present experiments is independently developed by Institute of Fluid Physics of CAEP. Its principle has been elaborated by Chang et. al\textsuperscript{[11]}. The image of the photographed object generated by the optical imaging component divides into identical 8 channels by the spectroscopic module. The scanning photography is completed by the scanning imaging module after 2 channels are imaged to the scanning slit of the scanning component through the coupling system. Another 6 channels are imaged to the framing imaging component through the coupling system to complete the framing photography.

3.2. Laser illumination technology for high-speed photography

The high-speed photography is an effective way to observe the process of high-speed movement. Amplifying the time course of the transient event, the transient variation and the 1D time and 2D spatial information can be directly reflected. Because of the high shooting speed and the short exposure time, the illumination is required for the high-speed photography. Compared to other illuminated light source such as the xenon lamp and the explosion light source, the laser has the advantages of strong penetrability, good monochromaticity and good imaging quality. Since the self-luminescence of the shooting object is usually a broad spectrum, the laser illumination and the narrowband filter are used to suppress most self-luminescence and the overexposure problem is effectively solved.

Because the imaging quality is seriously influenced by speckles and large number of interference fringes after coherent light beam spreading, high-power laser source failed to achieve good results in precision physics experiments. Recently, adopting the diffractive beam homogenization device and the multimode fiber light transmission and lens coupling beam expansion method, uniform illumination and clear imaging of 300 mm field laser are complemented\textsuperscript{[12]}. Though this method, the laser speckle and interference fringes are effectively suppressed and the problem of gradual halo of images of the shooting object in large field of view parallel beam illumination is solved.

Applying above technical achievements, the laser illumination and the narrowband filter are used in present experiments to avoid the overexposure and suppress the influence of the strong self-luminescence during the process of jets impact targets on the imaging quality. Therefore, clear images of the shock wave front and the debris cloud evolution are obtained, make it more precise to interpret velocities of the debris cloud and the shock wave front.

4. Results and analysis

Framing and streak pictures of the process of copper jets impacting LY12 aluminum targets are shown in Fig. 2 and 3. As can be observed from framing pictures, jets vertically impact targets in both experiments, and the images of the debris cloud and the shock wave front are discernible. The influence of the self-luminescence generated by jets impact targets on the imaging quality is successfully suppressed and the overexposure is avoided. The 2D spatial information of the generation of the debris cloud at the sample points of the framing images is given. In addition, comparing two
framing images and dividing the time span, the jet velocity (before and after impact targets), velocities of debris clouds and shock wave fronts can be calculated.

![Image](image1.png)

**Figure 2.** Framing and streak pictures of a copper jet impacting a 2 mm LY12 aluminum target

![Image](image2.png)

**Figure 3.** Framing and streak pictures of a copper jet impacting a 4 mm LY12 aluminum target

The horizontal axis of the streak picture is the time, while the longitudinal axis represents the position (at the horizontal symmetry axis of the framing pictures) of moving objects. As shown in Fig. 2, because the impact position coincides with the scanning position, the velocities of the tip of the jet after impact the target and the debris cloud front can be obtained from the streak picture. However, in another experiments shown in Fig. 3, because the scanning position deviates from the impact position, longitudinal velocities of shock wave fronts and debris clouds can be obtained from the streak picture.

The data processing of streak pictures includes three steps: extracting data points, calculating imaging magnification ratio and obtaining velocities. Firstly, continuous data points in the streak picture is extracted. Especially, extracted data points should be added at turning point. Secondly, according to the length of the scale and the size of the scale image on the streak image, the imaging magnification ratio of the transverse and longitudinal directions, $\alpha$ and $\beta$, are calculated. Thirdly,
combining $\alpha$ with the slit separation on the streak picture, the movement duration of the jet can be calculated; combining $\beta$ with the coordinates of points on the scanning trajectory, the movement distances of the jet, the debris cloud and the shock wave can be calculated and corresponding velocities can be obtained after dividing the scanning time.

Combining information of framing and streak pictures, the process of jets impact targets is comprehensively and completely recorded. Taking the experiment of a copper jet impacting a 2 mm LY12 aluminum targets as an example and applying above data processing method, the jet velocities before, during and after impact the target and the velocity of the debris cloud front can be calculated according to information of framing and streak pictures. As listed in Tab. 1, $V_{j/f}$ and $V_{d/f}$ are velocities of the jet and the debris cloud obtained from the framing picture; $V_{j/s}$ and $V_{d/s}$ are velocities of the jet and the debris cloud obtained from the streak picture; $\delta_j$ and $\delta_d$ are relative errors of information from the framing picture relative to those from the streak picture in velocities of the jet and the debris cloud. The velocity of the debris cloud is higher than that of the jet before impact. After impact, because the jet is in the debris cloud, the jet velocity is hardly interpreted.

Table 1. Framing and streak information of the process of a copper jet impacting a 2mm LY12 aluminum target: velocities of the jet and the debris cloud

| No. | $V_{j/f}$ / km*s$^{-1}$ | $V_{j/s}$ / km*s$^{-1}$ | $\delta_j$ | $V_{d/f}$ / km*s$^{-1}$ | $V_{d/s}$ / km*s$^{-1}$ | $\delta_d$ |
|-----|-----------------------|-----------------------|-----------|-----------------------|-----------------------|-----------|
| a-b | 8.140                 | 8.429                 | -3.43%    | --                    | --                    | --        |
| b-c | --                    | --                    | --        | 8.756                 | 9.317                 | -6.02%    |
| c-d | --                    | --                    | --        | 8.624                 | 8.775                 | -1.72%    |

It should be noted that, in framing pictures, before impact, the position of the jet can be identified by the leading edge of the bright part; after impact, the leading edge of the bright part should be identified as the debris cloud, because its velocity is higher than the jet velocity. In the streak picture, curves with the highest brightness before and after impacting targets correspond to jets and debris clouds respectively.

Based on the digital interpretation of framing and streak pictures, combined with the scanning speed and the imaging magnification ratio, velocities of the jet, the debris cloud and the shock wave on corresponding curves can be obtained.

5. Conclusion
In present paper, applying the utility of ultrahigh-speed simultaneous framing and streak photography technology, the experiment of copper jets impacting thin aluminum plates at hypervelocity is observed. Debris clouds and front edges of shock waves are clearly observed and recognized after using newly developed technology to effectively restrain excessive exposure caused by intensive self-illumination in the experiment. The process of jets impact targets is comprehensively and completely recorded by framing and streak. The methods of data processing are developed and the velocities of the jet and the debris cloud are obtained.

6. References
[1] Pickutowski A. Debris clouds generated by hypervelocity impact cylindrical projectiles with thin aluminum plates. International Journal of Impact Engineering, 1987, 5(1): 509-518.
[2] Chi R Q. Research and modelling of debris cloud produced by hypervelocity impact of projectile with thin plate. Harbin: Harbin Institute of Technology, 2010. (in Chinese)
[3] Wen K, Chen X W, Lu Y G. Research and development on hypervelocity impact protection using Whipple shield: An overview. Defence Technology 2020, doi:10.1016/idt.2020.11.005.
[4] Whipple F L. Meteorites and space travel. Astronomical Journal, 1947, 52(5): 131-131.
[5] Di D L, Chen X W, Wen K, Zhang C B. A review on the study of debris cloud produced by normal hypervelocity impact upon a thin plate. Acta Armamentarii, 2018, 39(10), 2016-2047 (in Chinese).
[6] Liu S, Xie A M, Huang J, Song Q, Luo J Y. Four sequence laser shadowgraph for the
visualization of hypervelocity impact debris cloud. *Journal of Experiments in Fluid Mechanics*, 2010, 24(1): 1-5 (in Chinese).

[7] Zhang C B, Di D N, Chen X W, Wen K. Characteristics structure analysis on debris cloud in the hypervelocity impact of disk projectile on thin plate. *Defence Technology*, 2020, 16(2), 299-307.

[8] Wen K, Chen X W, Chi R Q, Lu Y G. Analysis on the fragmentation pattern of sphere hypervelocity impacting on thin plate. *International Journal of Impact Engineering*, 2020, 146, 103721.

[9] Wen K, Chen XW. Failure evolution in hypervelocity impact of Al spheres onto thin Al plates. *International Journal of Impact Engineering*, 2021, 147, 103727

[10] Ang J A. Impact flash jet initiation phenomenology. *International Journal of Impact Engineering*, 1990, 10(1-4):23-33.

[11] Chang L H, He H, Wen W F, Gu Z W, Li Z R, Peng Q X, Wang X, Li J, Qian W X, Liu N W, Zhao X C, Wang W. Ultrahigh-speed simultaneous framing and streak photography of magnetic flux compression by explosive cylindrical implosion. *High Power Laser and Particle Beams*, 2015, 25(11): 115002. (in Chinese)

[12] Chang L H, Wang X, Wen W F, Song Z F, Wang W, Ran M J, He H, Gao P. New development of laser illumination technology for high-speed photography. *High Power Laser and Particle Beams*, 2018, 30(4): 040101. (in Chinese)