Detection of microparticles in dynamic processes

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Abstract. When a metal plate is subjected to a strong shock impact, its free surface emits a flow of particles of different sizes (shock-wave “dusting”). Traditionally, the process of dusting is investigated by the methods of pulsed x-ray or piezoelectric sensor or via an optical technique. The particle size ranges from a few microns to hundreds of microns. The flow is assumed to include also finer particles, which cannot be detected with the existing methods yet. On the accelerator complex VEPP-3–VEPP-4 at the BINP there are two experiment stations for research on fast processes, including explosion ones. The stations enable measurement of both passed radiation (absorption) and small-angle x-ray scattering on synchrotron radiation (SR). Radiation is detected with a precision high-speed detector DIMEX. The detector has an internal memory of 32 frames, which enables recording of the dynamics of the process (shooting of movies) with intervals of 250 ns to 2 µs. Flows of nano- and microparticles from free surfaces of various materials (copper and tin) have been examined. Microparticle flows were emitted from grooves of 50–200 µs in size and joints (gaps) between metal parts. With the soft x-ray spectrum of SR one can explore the dynamics of a single microjet of micron size. The dynamics of density distribution along micro jets were determined. Under a shock wave (∼ 60 GPa) acting on tin disks, flows of microparticles from a smooth surface were recorded.

1. Introduction

The process of emission of particles from a metal free surface (FS) under the impact of shock wave (SW) is of great interest [1–5]. Exposure of FS of matter to a SW results in development of microperturbations on the FS of metals and subsequent formation of a fine fraction, the size and speed of its particles varying in the space. The behavior of instability growth on the metal FS and thus the dust cloud characteristics depend on the phase state of the material, loading conditions, etc.

They at LASL [1,3] conducted a series of experiments with pressures at which a metal is in a mixed solid-liquid state in an unloading wave. The authors of the works showed experimentally...
that the mass of the emitted particles depends not on the SW pressure amplitude, but on the profile of the SW arriving at the free surface (FS) and parameters of initial perturbations. This result holds for metals passing to a liquid state under exposure to a SW. Using radiographic and piezoelectric techniques they at VNIIEF [4,5] obtained density distributions for particles leaving a free surface of lead. From considerations of quality, elongated grooves (slits) were used.

In this paper, the dynamics of density distribution along micro jets were determined via recording of passed SR from the VEPP-3 collider with a precision detector DIMEX [6] with a resolution of 100 nm. The SR application gives a notable advantage of a soft x-ray spectrum (a flow from a single groove can be investigated), stability of SR pulse parameters (the detector absorption can be calibrated after the experiment), high frequency of pulses (movies can be shot) and short pulse duration (less than 1 ns).

2. Experimental set-up
The motion of a micro jet arising from a groove (recess) in a metal disk (of copper or tin) was investigated. The disks were 24–30 mm in diameter and 2–5 mm thick. The groove dimensions varied from 30 to 200 µm. Micro jets emitted from direct or skew joints of two copper half-disks were also investigated.

Initiated with the help of the electrodetonator EDV-1, explosive plane-wave lens (1) creates a planar shock wave incident on explosive charge (2) 15 mm high, which loads a copper disc 1.2 mm thick (figure 1). On the upper end of the disk there is a groove to form a micro jet. The groove had a cross section of an equilateral triangle with a side from 30 to 200 µm (figure 2). This disk was accelerated by a HE charge 20 mm in diameter and 15 mm high (plasticized PETN with a density of 1.52 g/cm³).

The investigation was carried out at the station for research on extreme states of matter, which was built on the VEPP-3 collider (BINP SB RAS, energy: 2 GeV, magnetic induction in the wiggler: B = 2 T, current per bunch: 100 mA). The SR spectrum is shown in figure 3.
Figure 3. (1) spectrum of radiation from 2 T wiggler, (2) radiation spectrum after 5 mm of beryllium, (3) radiation spectrum after additional 5 mm of PETN, (4) radiation spectrum after 10 mm of PETN more.

Figure 4. Efficiency of x-ray photon detection versus photon energy $E$ for various pressures in detector DIMEX.

Figure 5. Experimental set-up. Radiographic recording over cumulative jet.

Figure 6. Radiographic shadow of disk flight. The $X$ axis is directed along with the disk motion.

Figure 4 shows the detection efficiency of the detector DIMEX [6], which was used for recording of passed SR. The one-coordinate gas detector DIMEX has 512 receiving channels (strips) 100 $\mu$m wide, which shoot a single frame. The internal memory of the detector enables recording of 32 frames (density distributions) with a time resolution of 250 ns or 500 ns. The VEPP-3 collider produces very stable SR pulses 1 ns long with a time interval of 250 ns. After the collimator, the SR flow is a flat strip 0.4 mm high and 20 mm wide. Due to high stability of SR pulses of the collider, the detector absorption can be calibrated before and after explosion experiments [7, 8]. Absorption in copper and tin was calibrated using foils 30–100 $\mu$m thick.

The absorption was recorded over a cumulative jet (figure 5). Figure 6 presents detector frames recorded during a flight of disk (without grooves) 5 mm thick. The record shows the position of the disk 0.5 $\mu$s later.
Figure 7. 50 µm groove in copper disk. Formation and motion of micro jet from left to right (N1251).

Figure 8. (N1250). Motion of micro jet from 100 µm groove from left to right. Copper disk (N1250).

Table 1. Jet mass (mg).

| Time          | Groove size |
|---------------|-------------|
|               | 50 µm | 100 µm | 200 µm |
| \( t = 1 \) µs | 0.25   | 0.56   | 0.8    |
| \( t = 2 \) µs | 0.22   | 0.56   | 1.45   |
| \( t = 3 \) µs | 0.14   | 0.5    | 0.97   |

3. Experimental results

3.1. Micro jets from grooves

During the explosion experiment (the set-up shown in figure 5), the start of the detector is synchronized with the SR pulse arrival and the position of the shock wave front in the sample. Calibration of detector absorption on the sample materials (copper or tin foil) yields the time dependence of the distribution of linear mass (mass along the SR beam) over the jet (figure 7, figure 8). In figure 7 each colored line represents the distributions of linear mass (mass along the SR beam) over the micro jet (one frame, a 50 µm groove). The frames were shot 0.5 µs after the beginning of the emergence of the micro jet.

Figures 8 and 9 show the dynamics of the mass distribution for a micro jet from a 100 µm groove. In figure 9 the jet moves from right to left. Figures 10, 11, and 12 show detailed linear mass distributions over the jet 1, 2 and 3 µs after (a 100 µm groove). The jet is being deformed strongly; the distribution amplitude divided by the density yields the transverse size of the jet. With \( \rho^*d = 0.024 \) g/cm\(^2\), the jet width is 30 µm. The total area under the distribution curve gives the jet mass. The dynamics of the total mass of the jet are shown in table 1 for 50 and 100 µm grooves. With a 100 µm groove, the total mass of the jet (in milligrams) stays virtually unchanged in the first 3 µs (0.56 mg per 1 mm in height). The mass of a jet from a 50 µm groove, decreases significantly (from 0.26 mg to 0.14 mg).

Micro jets from tin were produced using disks 20 mm in diameter and 5 mm thick. Explosive acceleration was formed with an identical HE charge (plasticized PETN, density of 1.52 g/cm\(^3\)). One 200 µm groove was made in the free surface of the disk. The dynamics of the jet mass...
distribution in the motion direction are shown in figure 13. The right column of table 1 shows the mass of micro-jet at times of 1, 2 and 3 \( \mu s \). Unlike a copper jet, the mass of tin micro jet varies strongly. The speed of the disk and the jet is equal to 1.84 km/s and 3.31 km/s, respectively (figure 14).

### 3.2. Micro jets from joints

Micro jets from a joint of two copper half disks were investigated (figure 15). The joints were of two types, rectangular (figure 15, left) and skew, with an angle of 45° (in the right). The copper disks were 24 mm in diameter and 2 mm thick. The acceleration was imparted by a plasticized PETN charge 20 mm in diameter and 15 mm high with a density of 1.52 g/cm\(^3\).

Dynamics of jet mass distribution in the direction of motion in case of rectangular and skew joints is shown in figures 16 and 17. The size and mass of jets from a rectangular joint are much larger than those from a skew one. The left- and right-hand columns in table 2 compare the jet mass values (mg per mm of height) at successive times. The central column shows the dynamics of the jet mass for a ground junction with half-disks pressed. Reducing the gap causes a several-fold decrease in the jet mass.
**Figure 13.** Mass dynamics on beam over jet (set-up 4.3) in experiment 1248.

**Figure 14.** $X-t$ diagram of motion of cumulative jet and tin disk. The disk and jet speeds are 1.84 and 3.31 km/s, respectively.

**Figure 15.** Assemblies for production of micro jets. Left: rectangular joint; right: skew joint.

**Figure 16.** Right joint. Cu. Experiment 1252.

**Figure 17.** Skew joint (45). Cu. Experiment 1258.
Table 2. Jet mass (mg).

| Time  | Rectangular joint | Ground rectangular joint | Skew joint |
|-------|-------------------|--------------------------|------------|
| $t = 1 \mu s$ | 0.454             | 0.242                    | 0.23       |
| $t = 2 \mu s$ | 1.182             | 0.238                    | 0.238      |
| $t = 3 \mu s$ | 1.244             | 0.268                    | 0.244      |

Figure 18. Position of tin disk without grooves at successive times.

Figure 19. Dynamics of distribution of mass of micro jet from tin.

3.3. Micro jets from smooth surfaces

Micro jets in the experiments were produced using grooves of different sizes. No jets from smooth surface of metal were detected. The situation changes when more powerful HE charges are used and the disk thickness is decreased. When a tin foil 30–50 µm thick is accelerated using pressed HMX (density of 1.88 g/cm$^3$), micro jets are clearly detected ahead the foil (figure 18). The speed of the foil is $U = 7.6$ km/s. The pressure in the tin is about 60 GPa. According to [9], the tin must pass to a liquid state. It is said in [3] that in this state the emission of particles increases considerably. The sizes of micro jets in the experiments were not measured. The linear mass along the SR beam is shown in figure 19. The experiment was conducted at atmospheric pressure, and thus the jets slowed down rapidly.

4. Conclusions

The experiments have shown that mass distribution from a single groove over the propagation and the dynamics of the total mass of jet can be recorded. Jets from grooves are strongly deformed in flight, and they cannot be regarded as a continuous medium—it is rather a flow of micro-particles of different sizes. The smaller is the size of the groove, the faster is the flow collapse. In case of tin, a large groove would also give an unstable flow.

In the experiments with jets from joints, the fitting of joint matters much; grinding of gaps leads to a several-fold decrease in the flow of microparticles.

Under a strong dynamic impact on tin ($\sim$ 60 GPa), its smooth surface also emits a flow of microparticles.

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