Dynamic registration of ejection from shock-loaded metals

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Abstract. This paper describes measurements of mass distribution along a microparticle jet with the use of synchrotron radiation (SR) from the VEPP-3 collider. The SR “soft” spectrum made it possible to measure microparticle jets of a record (minimum) density of about 1 mg/cm³. Simultaneous recording of microparticle jets using piezoelectric sensors made it possible to compare and mutually complement their readings.

1. Introduction
Investigations of the effect of shock wave loading on various materials reveal the effect known as dusting [1]. The essence of this effect is the formation of a cloud (jet) of micro and nanoparticles upon arrival of strong shock wave at a free surface (FS). In such interfaces there are spalling ruptures, caused by the tensile stresses that result from the interaction of the incident shock wave and the reflected one. Recording the dynamics of cloud of disperse-phase microparticles of matter in rapid gas-dynamic processes is a complex scientific and technical problem.

The first studies of these processes began at the RFNC-VNIIEF in the sixties, but they were published in 1998 [2]. Later on similar studies were carried out in Russia [1, 3, 4], USA, and France [5–8]. Great effort of the researchers focused on the development of periodic instabilities at high acceleration of FS [3, 9]. To date, this phenomenon still remains insufficiently studied, and the technique of conducting experiments is not quite perfect.

In recent years, a new wave of intense studies of dusting has begun [1]. This was facilitated by qualitative improvements (developments) of experimental techniques, including laser [5,6,10–13] and optical [4,6] ones, piezoelectric sensors [14,15], and radiography [1,16], as well as the emergence of new research methods, such as protonography [17] and synchrotron radiation (SR) detection [18–20]. The increased interest in this phenomenon is also in consequence of the effect
of “dusting” from FS at measurements of the dynamics of its motion with the use of transmission, electrocontact, and laser methods of motion recording, as well as importance in a number of physical processes, for example, in the problem of inertial fusion in plasma compression [21].

The studies of the “dusting” processes include a direction that considers the development of consequences of the Richtmyer–Meshkov instability in a metal (or a liquid) as the main source of the dust cloud. In experiments, the FS is subjected to periodic perturbations with different amplitudes [1, 9, 22, 23]. The purpose of these works is to identify how the perturbations on the metal surface and the amplitude and shape of shock wave affect the density distribution in space, the mass of ejected matter, the velocity of particles, and the particle size distribution.

One of the promising directions in investigating the dynamics of the dispersed phase in rapid processes is particle motion recording by the heterodyne laser interferometric technique (PDV). However, the reconstruction (decoding) of the record has some difficulties so far. This can be done via measuring jets of particles the size, mass, and form factor of which are known. In such experiments a layer of calibrated particles is applied to the free surface of projected plate, after which shock wave loading of the plate and boosting of the particles of the dispersed phase are carried out. Comparison of experimental data with calculation results makes it possible to verify the correctness of the calculation models and to obtain data on the dynamics of motion of particles with known parameters. These data can be compared with the results of recording of the dispersed phase in dusting processes where particle parameters are not known initially [24].

Most experiments focus on studying the ejection of particles in dependence on the shape and size of periodic irregularities (depressions and grooves) on the surface of metals [25–27]. The existing particle detection techniques allow determining the maximum particle velocities (optical, x-ray, and laser techniques), particle momentum (piezoelectric sensors), and microparticle sizes (optical and holographic techniques [10]. The greatest difficulties arise in the measurements of the mass distribution along the particle jet (especially in the region of low jet densities of 1–100 mg/cm$^3$).

In this paper, the detection of particle jet from a free surface of a metal was carried out with the use of SR from the VEPP-3 accelerators at Budker Institute of Nuclear Physics (Novosibirsk) [28]. The SR from VEPP-3 has a soft x-ray spectrum (8–30 keV), identical short pulses (less than 1 ns), and small divergence (less than 0.5 mrad), which allows detecting very low particle jet densities [29,30]. The high repeatability (identity) of SR pulses enables careful calibration of the DIMEX detector before and after the explosion experiment [31,32]. The accuracy of calibration of the detector makes it possible to identify the distribution of small masses of particle jet along their motion. In the experiments, the SR visualization of microparticles was carried out simultaneously with recording readings of piezoelectric sensors, which are applied widely due to their availability and ease of obtaining of information on dynamic flows of microparticles [33]. The main disadvantages of this technique consist in the difficulties of dynamic calibration of piezoelectric sensors. They should be used in conjunction with other techniques that can estimate the mass and velocity of jets. Using SR is an ideal complement to piezoelectric sensors. Correlation (comparison) of information on a microparticle jet (velocity and mass) on a microparticle jet with the magnitude of signal from a piezoelectric sensor enables independent calibration of sensor readings.

We studied jets of microparticles from grooves (irregularities) of 6 to 60 µm in size made on the surface of tin. A pressed HMX charge created a shock wave. The resulting mass distributions along the jet of microparticles are in good agreement with the calculations made at the RFNC-VNIIEF [1,16]. The obtained data are necessary for numerical simulation of the particle ejection processes.
2. Experimental setup

The experiments were carried out at the station Extreme state of matter of the VEPP-3 collider. The electron energy was 2 GeV, the SR spectrum from the 3-pole wiggler being in the range from 8 to 30 keV [28, 30]. A collimator shaped the SR as a strip 20 mm wide and 0.2 mm high. Figure 1 shows the position of the tin disk (FS) with grooves and the detector relative to the SR beam. The explosion-accelerated disk was moving along the DIMEX-3 detector [31], across the SR beam. The recording part of the detector consists of $0.1 \times 1.0 \times 3.0$ mm$^3$ (width, height, and depth) cells (strips). The total number of in the detector is 512, i.e., the recording zone is 51 mm long, the linear resolution being 0.1 mm. The high stability of radiation from the VEPP-3 wiggler enables calibration of the detector before and after the explosion experiment. Copper foils 15, 30, and 50 µm thick were used for calibration. The DIMEX-3 detector measured the transmitted SR distribution, from which the distribution of linear mass along the detector was calculated (the amount of matter along the SR beam, or $\rho d$, measured in g/cm$^2$). Recording of the distribution of linear mass (one frame) was performed each 124 ns with an exposure time of 1 ns. The DIMEX-3 detector can record 100 frames in total.

Figure 2 presents a photo of the experimental unit. A pressed HMX charge of a diameter of 20 mm and a length of 20 mm boosted a tin disk, the charge initiated by an explosive lens through an intermediate HMX charge. The total weight of the HE in the assembly (with the detonator) did not exceed 12 grams. The explosion unit was placed in the explosive chamber, which was pumped out before the experiment to a pressure of 0.01 atm. Some of the experiments were carried out under initial atmospheric pressure. In all the experiments, the detector and the piezoelectric detector were triggered using a wire sensor located in the explosive lens.

A piezoelectric sensor [33] recorded the pressure of the incident dust jet. The sensor with a receiving part diameter of 5 mm was located at a distance of 18, 29 and 36 mm ($H$, mm) from the FS (table 1).

Some roughness was milled in the tin sample FS; the roughness varied from experiment to experiment and consisted of grooves with a pitch $\lambda$ and depth $A$. Figure 3 displays a measured profile. The roughness has form of a strip of a width $L$ (figure 3). The rest of the free surface of the sample was polished. The thickness of all the tin samples was 3 mm; the diameter was 20 mm. The data on the values of $A$, $\lambda$, and $L$ of the grooves for the experiments performed are given in table 1.

Since the SR detection area (about 20 mm) was smaller than the distance from the FS to the piezoelectric sensor, the experiments were carried out in two set-ups. In set-up 1, the detector...
Figure 2. General view of experimental unit for shock loading of sample with the use of SR: 1—HE charge; 2—tin plate; 3—piezoelectric sensor.

Table 1. Initial data for the experiments: $A$ is the depth of groove roughness; $\lambda$ is the distance between grooves; $L$ is the width of roughness area; $P_0$ is the pressure in explosion chamber.

| Profile | $A$, $\mu$m | $\lambda$, $\mu$m | $L$, mm | $H$, mm | $P_0$, bar |
|---------|-------------|-------------------|--------|--------|------------|
| Rz6     | 6           | 50                | 20     | 18, 29 and 36 | 0.01 and 1.0 |
| Rz60    | 60          | 250               | 5      | 18, 29 and 36 | 0.01 and 1.0 |

recorded the initial motion of the FS, the formation of dust cloud, and the moment of impact (interaction of the dust cloud with the piezoelectric sensor). In set-up 2 (with large distances to the sensor), detected were either the initial stage of dust cloud formation or the moment of impact on the piezoelectric sensor.

3. Results of experiments
3.1. Experiments with $H = 18$ mm
The FS roughness was made in the form of the Rz6 profile. The detector field covers beginning of the motion of the FS and the impact of the cloud on the piezoelectric sensor. Figure 4 shows the distribution of the SR beam linear mass ($\rho d$) along the particle motion at the initial moment of cloud formation in vacuum. The FS begins to move at the time $t = 3.72 \mu$s. The coordinate $X$ is expressed in the detector channels. The initial position of the FS is 17.0 mm; the position of the piezoelectric sensor is 36 mm. The moment of the microparticle cloud impact on the piezoelectric transducer (time $t = 10.29 \mu$s) is shown in figure 5. The (linear) mass of the dust cloud at the moment of the impact is 1 mg/cm$^3$, which corresponds to an approximate bulk density $\rho = 0.7$ mg/cm$^3$; the diameter of the sensor is 0.5 cm. The head of the dust cloud is well
Figure 3. Profile of grooves in a free surface: $\lambda$ is the distance between grooves; $A$ is the depth of groove roughness; $B$ is the distance along grooves.

Figure 4. Dynamics of the mass distribution on SR beam ($\rho_d$) at initial time (time between frames is 0.496 $\mu$s), time counted from detector start (vacuum). The mass is negative because the experiments was carried out in vacuum and the detector was calibrated at atmospheric pressure.

Observed at a mass level of 1 mg/cm$^3$; according to these data, the $X$–$t$ diagram (figure 6) of the positions of the cloud and FS is created. The speed of the FS and of the cloud of microparticles was 2.80 and 3.28 km/s, respectively, in vacuum. In experiments under atmospheric pressure, the velocity of the cloud was 2.9 km/s. The red arrow indicates the moment (10.3 $\mu$s) when the dust cloud reaches the piezoelectric sensor in vacuum. This time agrees well with the signal rise time in vacuum on the oscillograph (figure 7).

Figures 8 and 9 show such data in experiments under atmospheric pressure in the explosive chamber. The FS and the sensor coordinates were 18 and 37.3 mm, respectively. The moment of impact of the cloud on the sensor ($t = 11.41 \mu$s) fully corresponds to the readings of the piezoelectric sensor (see figure 9), $t_2 = 11.45 \mu$s.
Figure 5. Mass distribution ($\rho d$) in particle cloud before impact on sensor (vacuum). The sensor position—$X = 36.0$ mm; cloud density at impact moment—1.0 mg/cm$^3$; total weight—8 mg.

Figure 6. Positions of the FS (black), jet (blue and crimson), and sensor (gray): $X$ is their coordinates (relative to the detector); $D$ is the velocity of dust cloud; $U$ is the FS velocity.

3.2. Experiments with $H = 29$ mm

Figure 10 displays the initial stage of formation of microparticle cloud from roughnesses for Rz60 ($\lambda = 250$ µm and $a = 60$ µm). Figure 11 shows the $X$–$t$ diagram of the cloud motion. The FS velocity was 2.78 km/s, the initial velocity of the jet also having increased and being 3.91 km/s. In a distance of 29 mm, it drops to 3.51 km/s, reaching the piezoelectric sensor at the moment of 10.8 µs. Figure 12 shows the oscillogram of the piezoelectric sensor. It displays two signal rises: the first is from the jet (time of 10.8 µs), and the second is from the impact of the FS (time of 14 µs). In the experiments under atmospheric pressure, the FS and jet velocities were
Figure 7. Oscillogram of signal from piezoelectric sensor (in vacuum). Signal on sensor begins to grow after 10.3 µs. Time counted from the detector starts.

Figure 8. Mass distribution ($\rho d$) in particle cloud before impact on the sensor (vacuum). The sensor position—$X = 36.0$ mm; cloud density at impact moment—1.0 mg/cm$^3$; total weight—8 mg. Time moments: 1—11.04 µs; 2—11.29 µs; 3—11.41 µs; 4—11.66 µs; 5—11.91 µs.

2.70 and 3.67 km/s, respectively. The region of the piezoelectric sensor was out of the recording zone in these experiments.

Figure 13 shows the dynamics of mass distributions at the moment of the impact of the jet and the FS on the sensor in a distance of 45 mm, and figure 14 presents the oscillogram of the signal from the piezoelectric sensor. The sensor started writing the signal at 24.8 µs. In another 4.1 µs, the signal started rising even more (the moment of impact of the FS on the sensor). The pressure of the dust jet (cloud) on the sensor ($\rho U^2$) is 6.4 MPa. The total mass ejected (from 35 to 42 mm) was 24 mg at the time $t = 25$ µs.
3.3. Mathematical modeling

The simulation of the particle ejection process was carried out at the RFNC-VNIIEF [9, 22, 23, 34]. The calculations relied on the model of development of the Meshkov–Richtmyer instability and the detachment of metal particles upon excess of the strength limits (figure 15). Detonation of pressed HMX charge created a shock wave (SW) in a tin disk. Considered were initial periodic irregularities with $A = 3 \mu m$, $\lambda = 50 \mu m$ and $A = 50 \mu m$, $\lambda = 300 \mu m$. The calculations yielded the profile of the shock wave in the sample, the velocity of the free surface of the sample, the velocity of the particle front in vacuum, and the total calculated mass ejected (table 2). The measured values for Rz6 and Rz60 are given in the parentheses.
Figure 11. Position of jet and FS (tin) in experiments 3 (vacuum) and 6 (air). The jet reaches sensor at 10.8 $\mu$s, and the FS reaches sensor at 14 $\mu$s; $D$ is the velocity of dust cloud; $U$ is the velocity of FS.

Figure 12. Record from the piezoelectric sensor: arrows—beginning of signal rise from dust cloud (10.8 $\mu$s) and from the impact of FS (14.0 $\mu$s).

Figure 16 shows the calculated profile of SW in the tin; figure 17 shows distribution of the mass of particles along the jet 1 $\mu$s after the start of the motion of the FS (for Rz60).

3.4. Discussion of results
Experimental data on a dust cloud escaping from a shock-loaded lead have been presented [1,23]. The radiography was done along the grooves on a sample about 10 cm long. The general form of the observed mass distributions along the jet coincides with the distributions obtained in this paper. A more detailed examination shows the density distribution in the dust cloud to
Figure 13. The jet mass distribution before impact on the piezoelectric sensor ($t = 24 \mu s$) and at the impact moment ($t = 25 \mu s$), as well as at the moment of impact of FS ($t = 28 \mu s$). Sensor position—$X = 45$ mm.

Figure 14. Record from the piezoelectric sensor: arrows—beginning of signal rise from dust cloud (24.8 $\mu s$) and from the impact of FS (28.8 $\mu s$).

... strongly alter in time. Whereas it is smooth in the initial period (figures 4 and 10), it is highly inhomogeneous before the impact on the sensor (figures 5 and 8). The velocity of the cloud motion falls from 3.91 km/s in vacuum to 3.67 km/s in air. Depending on the profile of the irregularities, the velocity of the cloud increases with the amplitude of the grooves.
Figure 15. Qualitative picture of development of instabilities and subsequent “dusting”.

Table 2. Calculated parameters of dusting in vacuum for tin samples with Rz3 (A = 3 µm, λ = 50 µm) and Rz50 (A = 50 µm, λ = 300 µm): h is the thickness, d is the diameter of the sample; some measured values are given in parentheses.

|               | Rz3       | Rz50      |
|---------------|-----------|-----------|
| h = 3 mm, d = 20 mm |           |           |
| Calculated pressure in SW front | 48 GPa   | 48 GPa   |
| Gradient dP/dx behind SW front | 75 GPa/cm | 75 GPa/cm |
| Velocity of FS of sample | 2.72 km/s (2.80) | 2.72 km/s (2.78) |
| Velocity of particle front in vacuum | 3.15 km/s (3.28) | 3.85 km/s (3.91) |
| Total calculated ejected mass | 9.55 mg (8) | 44 mg (24) |

Figure 16. Profile of SW in sample (tin).

One can note very the good agreement between the calculations and the experiment, especially with Rz60 (right column in table 2). The difference is only in the total mass of the cloud (the calculation gives 44 g, and the experiment 24 g). The value of the momentum (pressure) of the cloud on the sensor at the moment of impact (ρU^2) was 9.0 MPa in vacuum and 6.4 MPa under atmospheric pressure.

It should also be noted that because of the method used to initiate the HE charges, the shock waves arriving at the FS were spherically diverging and so was the dust jet; some particles ejected from the FS passed by the SR beam. Therefore, the dust jet parameters measured by
Figure 17. Distribution of mass on SR beam 1 μs after motion of FS.

Figure 18. SR recording scheme for transverse arrangement of assembly.

the detector are valid only for a plane jet, and the calculation of the dependences of the density on the coordinate under the assumption of a one-dimensional jet yields underestimated values of the density.

The lateral expansion of the dust cloud was recorded in the set-up presented in figure 18. The tin disk (FS) was moving upwards, across the SR plane. The detector successively registered the cross section of the cloud with an initial distance from the FS of 10 and 30 mm. One can see in figure 19 (H = 10 mm) that the density distribution is spherically symmetrical. According to the estimation of the cloud expansion, the diameter of the cloud (on the SR beam) decreases from 20 to 14 mm in a distance of 30 mm from the FS. Therefore, the measured mass of the cloud around the piezoelectric sensor is 0.7 times less.

One can also see the dependence of the cloud velocity on the Rz value. Increase in the roughness results in increase in the ejected dust mass and velocity. In the calculations we used the Rz3 and Rz50 values, and in the experiments the Rz6 and Rz60 ones. This can explain the larger discrepancy in the results in the first column in table 2. The calculated and
experimental data on the mass distribution along the jet (1 \( \mu s \) after) completely coincide (figure 4 and figure 17).

Figure 17 shows good agreement between the measurements of the dynamics of the dust cloud density by the SR method and with the use of the piezoelectric sensor. Records of density measurements by both the methods are superimposed here.

4. Conclusions
Experiments on simultaneous recording of the jet position using SR and a piezoelectric sensor have been carried out. Our deductions are as follows:

- FS and jet velocities in vacuum and under atmospheric pressure have been obtained. The jet velocities in vacuum exceeded those under atmospheric pressure by 0.3–0.4 km/s.
- The jet velocities and ejected masses for Rz60 are higher than those for Rz6.
- The density distribution over the jet cross section has been obtained. The side edges (3 mm on each side) of the FS are strongly deformed (curved) in the flight.
- In larger distances, the jet velocity decreases faster under atmospheric pressure.
- The density distribution in the cloud at the moment of impact on the piezoelectric sensor has been obtained.
- The reliability of the measurement of the dust cloud parameters using piezoelectric sensors has been shown. This measurement method is the simplest and easiest to perform.

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