Experimental study of ejection of particles from shock-loaded metals

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Abstract When a strong shock wave reaches a free surface of metals, there occurs ejection of microparticles from the surface. The number and size of particles depend on the metal, finishing of its surface, incident wave shape, and many other factors. Most experimental studies investigate the particle ejection in dependence on the shape and size of irregularities (notches and grooves) on the surface of metals. The resulting data are necessary for numerical simulation of particle ejection processes. The existing methods of particle detection enable determination of the maximum particle velocities (optical, X-ray, and piezoelectric sensors), particle momentum (piezoelectric sensors), and microparticle sizes (optical and holographic sensors). The greatest difficulties arise in the measurement of the particle mass distribution and particle distribution by size. In this paper, the mass distribution along the jet was measured using the "soft" synchrotron radiation spectrum of the VEPP-3 collider.

1 Introduction

When a strong shock wave reaches a free surface (FS) of a metallic sample, there occurs ejection of the front part of the sample in the form of a particle flow [1-7]. Tensile stresses that result from the interaction of incident and reflected shock waves cause spalling. A real FS always has some small irregularities, and stresses that concentrate in them make microparticles tear off the FS. Initial separation of particles from both micro-depressions and micro-hills is considered in the literature [2]. When a sample melts under shock wave loading, there arise tensile stresses in the liquid medium, which leads to formation of an expanding cloud of liquid particles [2-4]. Experimental study of these processes is very difficult because of the small size of the microparticles and their high flight velocities. Despite the great effort made to register this phenomenon, the total mass of particles ejected from an FS, its distribution and evolution along the motion in time, and the dynamics of particle sizes in the flow are still unclear [1-2].

The present work investigates flows of microparticles from a shock-loaded copper disk. Single grooves with a characteristic size of 50 μm were made on the copper disk surface. The flows from junctions (joints) between copper plates were also investigated. The particle fluxes from the copper disk FS were recorded using the synchrotron radiation (SR) from the VEPP-3 collider at Budker Institute of Nuclear Physics. (Novosibirsk). The SR from VEPP-3 has a soft x-ray spectrum (up to 30 keV), identical short pulses (less than 1 ns), and small divergence (less than 0.5 mrad), which allows registering very low particle flux densities. The high repeatability of the SR (in terms of time and spectrum) enables thorough calibration of the detector before and after an explosion experiment. The accuracy of the calibration of the detector makes it possible to determine the distribution of the mass of the particle flux along the particle motion.

2 Experimental set up

The experiments were carried out at the station "Extreme state of matter" at the collider VEPP-3. The electron energy was 2 GeV, and the SR spectrum from the 3-pole wiggler is given in [8-9]. A collimator in the form of a strip 18 mm wide and 0.1 mm high formed the SR. The position of the copper disk (FS) with grooves and joints and of the detector relative to the SR beam is shown in Fig.1. An explosion-accelerated copper disk was moving along the detector [10] and across the SR beam. The size of one detector channel is 100 μm in length and 200 μm in height. The detector was recording the distribution of the passed SR (512 channels per frame) with an exposure of 1 ns. The VEPP-3 collider is able to produce one SR pulse in 250 ns (one-bunch mode) and 125 ns (two-bunch mode). The latest modification of the detector allows recording 100 frames.

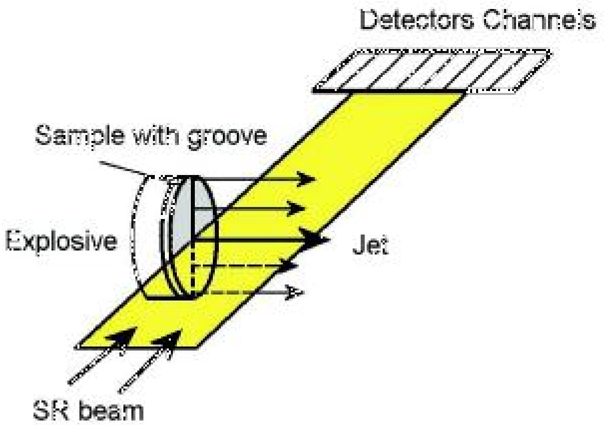

Fig. 1. Arrangement of sample, detector and SR plane.

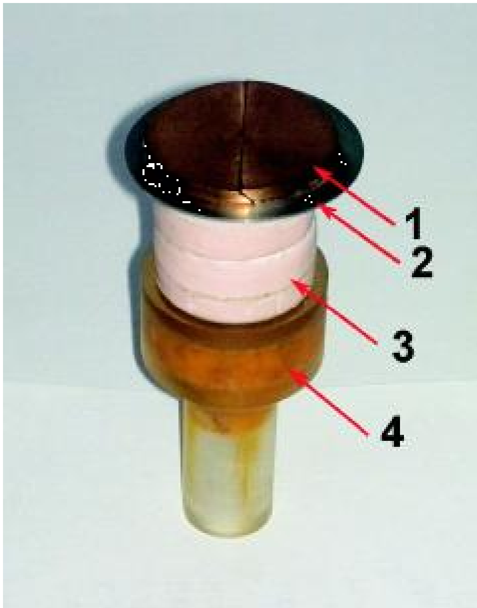

Fig. 2. Experimental assembly. 1- disk with oblique joint, 2 - substrate, 3 – HE charge, 4 - explosive lens.

Fig. 2 presents a photo of the experimental assembly. The explosive lens initiated a plasticized PETN charge (20 mm in diameter and 20 mm in length). The total weight of the HE in the assembly with the detonator was 12 grams at most. The explosion unit was placed in an explosive chamber, which was pumped out before the experiment to a pressure of 0.05 atm. In all the experiments, the detector was initiated from a wire sensor located in an explosive lens.

The free surface (FS) of a copper (grade M1) sample had irregularities in the form of a groove (flute) with a width and depth of 50 μm and joints between the half-disks (Fig. 3). The joints were normal, oblique and stepwise. The gaps between the joints were within 50 μm. The thickness of all the copper samples was 2 mm, and the diameter was 20 mm. The shock wave was transferred to the copper disk through a 12N18X10T steel gasket 0.5 mm thick of 30 mm in diameter.

Since the SR detection area was ~ 14 mm, the motion of the jet at large distances was investigated with displacement of the detector from the disk by a strictly determined distance. The adjustable delay of the detector start made it possible to show the distribution of the jet at large distances.

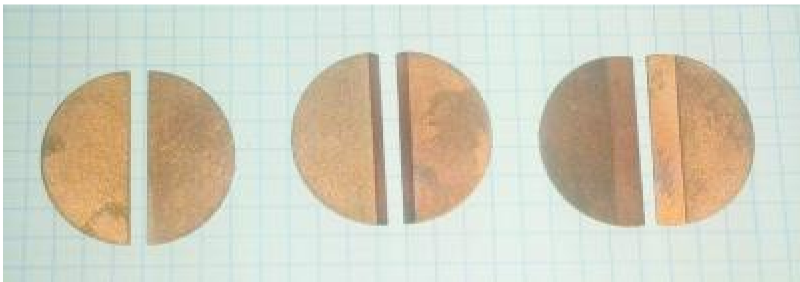

Fig. 3. General view of plates with joints. Lef t: normal joint, center: oblique joint, right: ste pwise joint. M1 copper of 30 mm in diameter .

Fig. 4. Sample with normal joint on 12N18X10T steel gasket.

3 Results of experiments

Fig. 5. displays the distribution of the mass along the jet in the period of 0.5 µS to 3.5 µS after the start of the copper disk movement. In the experiments, the frames were shot with an interval of 0.5 μS, but Fig. 5 shows them with an interval of 1 μS. Calibration of the detector absorption using copper foil makes it possible to register the mass on a beam> 0.001 g/cm^2. The black line indicates the limit of mass measurement on the beam. The figure shows a strong heterogeneity of the mass distribution along the direction of motion. The jet is a stream of microparticles, not a continuous medium. After 1.5 μS, the visible jet length is ~ 2.5 mm.

Fig. 6. presents X-t positions of the jet and copper disk. The X coordinate is counted from the FS of the disk. The initial velocity of the disk is 1.81 km/s, and the particle flux velocity is 2.8 to 3.86 km/s.

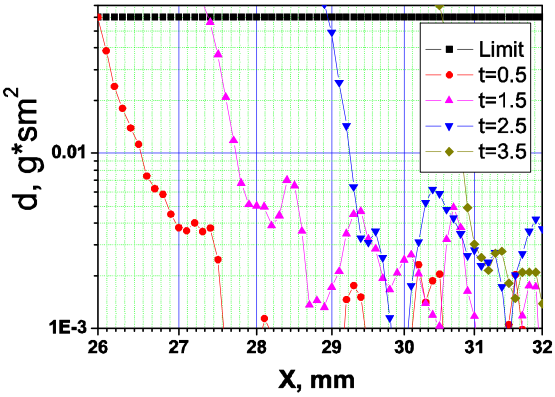

Fig. 5. Dynamics of mass distribution on SR beam (frames taken with interval of 1 μS); 50-μm groove.

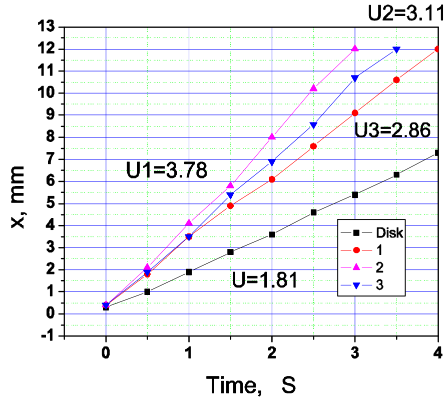

Fig. 6. X-t diagram of position of disk and jet from joints. 1-oblique joint, 2-normal joint, 3-stepwise joint.

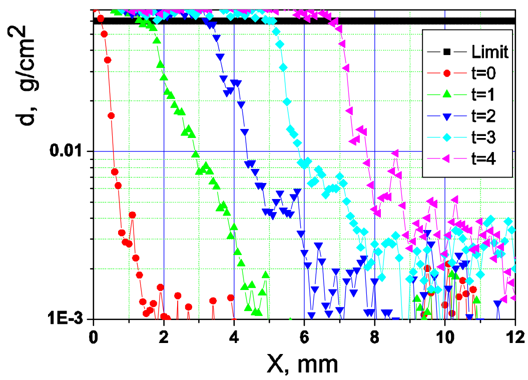

Fig. 7. Dynamics of mass distribution on SR beam at the initial stage (frames taken once in 1 μS); normal joint.

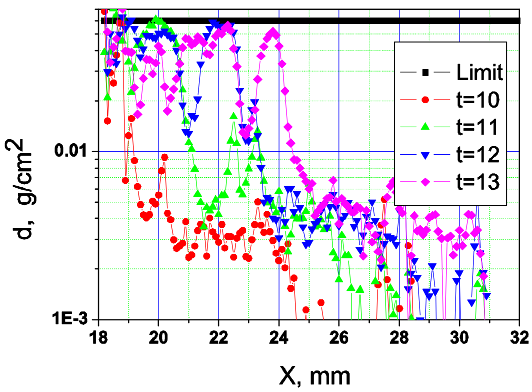

Fig. 8. Dynamics of mass distribution on SR beam at later times; normal joint.

Fig. 7 shows the distribution of mass along the jet from the normal joint at the initial stage of motion (1 to 4 μS). Fig. 8 demonstrates the mass distribution at later times (10 to 13 μS). At these times, we see separation of particles with large mass.

Integration of the resulting mass distribution along the motion yields the total mass of particles ejected from the FS. Table 1 shows the mass of the particles as a function of time for the copper surface irregularities studied. The data are given for a jet height of 1 mm. The jet from the oblique joint has the least mass. The normal joint yields the largest ejecta. The total momentum of the ejected mass is 0.02 to 0.057 kg m/s for different joints.

Table 1.

	The mass of the ejecta, mg/mm			
Time, mS	Groove	Normal junction	Oblique junction	the junction of the step
1	0.25	0.454	0.242	0.323
2	0.22	0.882	0.438	0.638
3	0.35	1.221	0.668	0.944
4	0.541	1.521	0.878	1.134

4 Discussion of results

Experimental data on a dust cloud escaping shock-loaded lead are presented in [1-2]. The radiography was performed along the grooves on a sample about 10 cm long. The mass distribution was derived using measurement interpolation. The form of the obtained mass distributions along the jet coincides with the distributions learned in this paper. Using SR from VEPP-3 made it possible to measure the distributions of the particle flux mass along the motion with an accuracy of 5% for densities of up to 0.001 g/cm^2. Frame-by-frame snapshots (Fig. 5) of the particle flux show deformation of the density distribution along the jet (frames t = 1.5, t = 2.5, and t = 3.5) in time.

The mathematical modeling of the particle ejection process was carried out at VNIITF. The calculations yielded the shock wave profile in the sample; the velocity of the free surface (FS) of the sample was 1.8 km/s; the velocity of the front of particles in the vacuum was 2.8 km/s.

According to the data in Fig. 5, the total mass of the particles is 5.4 mg/cm^2, which is in good agreement with the data in [1-2]. The particle momentum transferred to the piezoelectric sensor can be calculated more accurately from the data in Fig. 5 (up to 0.057 kgm/s). The obtained mass distributions also enable more accurate calibration of the readings of the piezoelectric sensors, and thus the mass and momentum of the x particle flow can be measured more accurately [2].

To increase the accuracy of measurements one can rise the frame rate of the detector (the VEPP-3 collider is able to produce SR pulses with an interval of 125 ns) and perform shooting from different projections.

5 Conclusions

The SR experiments on recording of absorption of jet made it possible to measure the mass distribution along the stream of microparticles to within 0.001 g/cm^2. The mass distribution along the jet is inhomogeneous yet on average coinciding with [2] and the calculations. New data have been obtained with a disk accelerated through a steel gasket; they supplement the results in [11-12]. The positions of the FS and the jet have been measured in dependence on time, and the dynamics of their velocity have been obtained. The resulting values make it possible to calculate the total momentum of the microparticle flow, which varies from 0.92 to 0.057 kgm/s for different junctions. These data will help to more accurately calibrate piezoelectric sensors, which are often used to study microparticle fluxes [1-2], and more accurately define the mathematical model for calculating the processes of development of instabilities and formation of microparticle fluxes.

Acknowledgment

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