Computational and experimental research of explosive meteorial devices with combined cumulative liners of the semi-sphere-cylinder shape

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Abstract. On the basis of numerical modeling within the two-dimensional axisymmetric problem of continuum mechanics and experimental studies, the features of the formation of high-speed compact elements using cumulative charges with liners of the combined form have been analysed. Such liners may have a jet-forming part in the form of a hemisphere, a slightly stretched semi-ellipsoid or a truncated sphere and an ellipsoid, as well as a cutting part in the form of a cylinder. The constructive solutions promoting increase in mass and high-speed parameters of the compact element formed by explosion are proposed. The variants of steel combined cumulative liners as a part of an explosive device provided the formation of non-gradient elements with a mass from 15 to a fraction of a gram moving at speeds from 7.5 to 10 km/s respectively are defined. Such fairly simple explosive devices can be used to simulate, in terrestrial conditions, single and group effects of micrometeorites and fragments of space debris on rocket and space equipment.

1. Introduction
In previous papers [1-3], the results of numerical simulation of the formation and motion of a non-gradient high-speed compact element which is formed during the operation of explosive projectile devices with combined shape charge liners were presented.

Such liners consist of a jet-forming part that forms the jet flow of material during the collapse on the axis and subsequent movement along the axis, and the cutting off part that separates its high-velocity part from the general flow of material.

2. Numerical calculations and experimental researches
Three main forms of the jet-forming part of such cumulative liners were studied: constant and degreasing (from top to base) thickness: hemispherical (HC-facing version), semi-ellipsoidal (SEC-facing version) and in the form of a truncated sphere (SC-facing version). To cut off the low-velocity part of the jet, a cylindrical part of this liner adjacent to the jet-forming part was used.

As the base liner designed for the subsequent comparison, a PC-liner with a hemispherical jet-forming part of constant thickness was chosen for which experimental data were previously obtained [4]. Figure 1 shows different designs of such degressive thickness liners made of steel.
Figure 1. Constructional schemes for liners: a – HC-liners, b – SEC-liners; c – SC-liners

Numerical simulation was performed by using two methods. The first was developed in BMSTU and realize a computing algorithm of free Lagrangian points (it’s name " ERUDIT " – “Heuristic Calculation of the Ordered Movement of Individual Points”). This method does not take into account the destruction of the material during the formation of a high-speed compact element. The second method is based on the ANSYS Autodyn program complex, in which it is possible to take into account the destruction of the material.

Figure 2 shows an example of the results of calculations the base variant of the PC-facing (Figure 1, a) by the method of the BMSTU (without taking into account the destruction of the material).

It can be seen that the stretched cumulative jet follows after the allocated gradientless high-speed compact element, that is a consequence of the absence of criterion of destruction of material in the calculations. As appears from the known results of the experiments [4] and numerical calculations taking into account model of destruction of material which are carried out according to the ANSYS Autodyn program instead of such "integral" jet the plume of the small particles scattering in the radial direction. This jet is gradually lagging behind from the moving compact element that moves faster than it.

Figure 3 shows a comparative pictures of the process of formation and movement of high-speed compact elements obtained from the results of calculations performed by the ANSYS Autodyn program without taking into account (a) and taking into account material destruction (b) [5].
Figure 3. The process of formation and movement of a high-speed compact element in the ANSYS Autodyn program: a - without material destruction; b - taking into account the criterion of destruction

Table 1 shows the comparative data of the calculations, given by both methods [5]. It can be seen that the discrepancy in velocities is less than 6%, which indicates the reliability of the results obtained.

| Embodiment | Geometric parameters liners, mm | Estimated speed of the element V, km/s |
|------------|---------------------------------|---------------------------------------|
| Base liner | \( R_0 \) \( \delta c \) \( R_1 \) \( \delta_1 \) \( R_2 \) \( \delta_2 \) | «ERUDITE» ANSYS Autodyn |
| HC-1       | 25.0 1.5 25.0 2.5 25.0 1.5     | 10.1 10.5                             |
| HC-2       | 25.3 1.2 25.3 2.5 25.3 1.2     | 10.1 10.5                             |
| SEC-1      | - 1.2 - 2.4 30.6 1.2           | 7.85 7.4                              |
| SEC-2      | - 1.0 - 2.4 26.6 1.0           | 10.4 9.8                              |
| SC-1       | 14.0 4.0 25.0 2.5 26.5 1.5     | 7.6 7.5                               |
| SC-2       | 15.0 3.0 25.0 3.0 26.0 1.5     | 8.1 8.0                               |
| SC-3       | 16.8 1.2 25.3 3.5 25.5 1.2     | 10.0 10.3                             |

As it was pointed out in [1-3], the aim of the study was to identify the design of combined cumulative liners, which make it possible to increase the speed of throwing a compact steel element of gram mass to a level of \( 8 ... 10 \text{ km/s} \). From these positions influence of design characteristics of the liners on mass and high-speed parameters of a high-speed compact element was investigated (Figure 1).

At the same time, the method of mass-velocity distributions (MVD), which was described in detail in [2], was used as the main tool for the results comparison. Figure 4 shows an example of this approach which is given in the analysis of SC-lining of various geometric parameters.

The curves on Figure 4 represent following ordinates of each point correspond to the mass of material of the facing moving with an axial speed, which is bigger than the value set by an abscissa of this point. Taking into account the provided rule of creation of MVD the curves corresponding to them always monotonically decrease with growth of speed and have a break on abscissa axis at a certain value which fixes the maximum speed of a jet flow– there are no material particles with a speed above this value in a jet flow. On the steepness of MVD in the vicinity of her point break it is possible to estimate the sizes of the head section of the flow– the more abruptly the curve goes from its extreme right point on the abscissa axis (towards lower velocities), the more massive this section is. With the use of the MVD method it is possible to trace clearly the fact of formation of an ungradient head section of the current is clearly traced, which, if preserved in its continuity, can later become a high-velocity compact element.
Figure 4. Mass-velocity distributions in the formation of a high-speed compact element from the SC-facing (Figure 1, c, Table 1):
1 – base liner ($\delta_1/\delta_2 = 2,5/2,5$ mm; $\delta_C = 3,2$ mm);
2 – SC-1 ($\delta_1/\delta_2 = 2,5/1,2$ mm; $\delta_C = 4,0$ mm);
3 – SC-2 ($\delta_1/\delta_2 = 3,0/1,5$ mm; $\delta_C = 3,0$ mm);
4 – SC-3 ($\delta_1/\delta_2 = 3,5/1,2$ mm; $\delta_C = 1,2$ mm);

In this case, a segment close to the vertical line on the MVD curve emerging from its extreme right-hand point on the abscissa axis (the presence of a vertical section means that some finite mass of the jet flow has the same axial velocity) is appeared. The ordinate of the upper point of this section, where the MVD curve undergoes a break at the transition to monotonous increase with decreasing velocity, corresponds to the mass of the formed compact element.

In the present study it was revealed that the main reason for increasing the speed of compact elements is the transition to the degressive thickness of the jet-forming (top) part of the cumulative liner. Simultaneously with the increase of liner thickness difference the gradient of the axial velocity in the head part of the jet also increases, which leads to a rapid decrease in the thickness of the head part due to its stretching and, as a consequence, the mass of the head part of the jet flow decreases [2].

Velocity increase can be explained by the spherical cumulation process [6, 7]. When the top part with degressive thickness collapses, conditions which are closer to the spherically symmetric one are created, i.e. the effect of spherical cumulation (the concentration of energy in the inner layers of the collapsing spherical shell) increases. In the case of explosive compression of a hemispherical liner of constant thickness, these conditions are violated due to the advancing motion of its vertex part, which is associated with an earlier arrival of a detonation wave to a liner and the beginning of its loading. Thus, reducing the thickness of the peripheral part of the hemispherical liners leads to an increase of its velocity, and the effect of a liner "reversing" appears to a lesser extent, thereby providing better conditions for the realization of spherical cumulation.

To increase the mass of the head part of the jet flow, it was determined that the shaping of the slightly elongated half-ellipsoid shape (Figure 1, b) leads to a decrease in the velocity gradient at the head section. Reduction of the velocity gradient of the head part in turn leads to an increase in the transverse dimensions of the element being formed while maintaining its speed. From Table. 1, which summarizes the results of the calculations, it can be seen that the best speed results were obtained for the HC-2, SEC-2 and SC-3 variants, while in the SEC-2 version the mass of the elements is minimal and amounted to fractions of grams, whereas in the variants of SC-3, it has already increased up to 5 g. However, from the technological point of view, the most suitable variant for realization is a variant of SEC-liner with a hemispherical shape of the jet-forming part (Figure 1, a), for which a variant of the technological process was proposed in [8], namely, stampings by plastic metal.

To validate the numerical calculation results the experimental researches were carried out [9]. The model of the explosive throwing device for tests is presented on Figure 5. Cumulative liner of HC-1
option was investigated (Table 1, Figure 1, a). As the basic method of experimental research, an x-ray method with luminescent memory plates was used [10].

![Figure 5. Model of an explosive throwing device for experimental researches: 1-place of initiation; 2-back cover; 3-case; 4-charge of explosives; 5-combined SEC-liner; 6-front cover](image)

As X-ray studies have shown, explosive compression of SEC-liners of a degressive thickness produces, a flow of the high-velocity particles gradually dissipating in the radial direction with a leading particle moving along the explosive charge axis. The X-ray picture pattern shown in Figure 6 corresponds to the time when the leading particle was located at a distance of about 0.7 m from the base of the shape charge with the cumulative concavity. In this experiment, its speed was 7.8 km / s and it had the following dimensions – a length of about 8 mm, a diameter in the middle section of about 3 mm [9, 10].

![Figure 6. X-ray picture of the motion of high-velocity element formed during explosive reduction of a steel SEC-liner of a degressive thickness](image)

It can be seen that at a certain distance from the leading element the scattered cloud of particles moves (coming in the recorded timepoint to the electrocontact sensor which is in the field of shooting). Obviously, the picture in Figure 6 is completely consistent with the principle of “work” SEC-liner. The leading particle is a cut off head portion of the jet flow of the material formed during the reduction of the hemispherical part of the SEC-liner, and the cloud of particles moving behind it is the result of material destruction during the collapse of the cutting off cylindrical part.

Based on the results of numerical calculations (see Table 1), a similar scheme with SEC-liner formed a compact element at a speed of 8.1 km/s. Thus, the discrepancy with experimental data on the speed of the formed compact element was 4%, which confirms the reliability of the numerical calculation method used by the authors.

3. Conclusion
As follows from the results of the experimental research, the transition to a SSC-liners of a degressive thickness made it possible to significantly increase the velocity of the cut off head part of the jet flow formed in the reduction of the hemispherical part in relation to the base SSC-liner of constant
thickness (increment of the velocity from 35%). The significant decrease in the dimensions of the leading element, as compared to the dimensions of the compact element formed by the base SSC-liner, was also predicted in the results of numerical simulation [1-3]. Moreover, it was shown in these researches that an increase in the "massiveness" of the head part of the jet flow with an increased velocity provided by the degeneracy of the thickness of the jet-forming part of the combined liner, can be achieved by making this liner's part the shape of the truncated sphere (Figure 1, c) or by the elongated half-ellipsoid (Fig. 1, b). Experimental verification of these improvements is the subject of a further research.

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