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Spatial Distribution of Mass and Speed on Movement of Two Shrapnel Discs of Variable Thickness in Explosive Load

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ABSTRACT

Results of studies of the explosive expansion of a set of shrapnel discs of natural crushing are described in the article. Set consisted of two disks of different thickness, but of a fixed total mass. The studies were carried out by computer simulation of shock-wave processes in a continuous formulation using the ANSYS/LS-DYNA program. The program of computer design foresees development of three-dimensional certainly-element model including, in accordance with symmetry of the examined system fourth part of the examined explosive system of casting block, with imposed on its knots of the proper scopes terms concerted with taken mixed Lagrangian-Eulerian approach within the framework of the continuum model. The effect of the order of installing disks of different thickness on the distribution of their mass and its velocity in the middle of the meridional angle of expansion is established. The analysis of the computer simulation presented on the basis of numerical studies on the distribution of the mass of the disks and its velocity of motion suggests that to create a narrow high-speed uniformly filled fragmentary mass of the axial flow, it is necessary to change the geometric shape of the disc so that in the central angular zones of the disks. This allows the velocity of the fragment mass to be aligned along the radius of the discs and to fill the first angular zones with the required mass of fragments.

Keywords: Explosive-technical examination; Numerical modelling; Explosion; Improvised explosive device; Shrapnel field; Spatial distribution of mass

1. INTRODUCTION

Unfortunately, the number of terrorist acts committed using a variety of explosive devices (ED) in the world is constantly increasing. One of the main factors affecting victims of such ED is the high-speed explosive fragment flow, which is formed either as a result of destruction of the ED body, or with the help of its damaging elements (nails, nuts, washers).

During the forensic explosion technical analysis, the forensic expert should answer a variety of questions, including[1]:

- The method of ED manufacturing and its elements (improvised *vs*. Industrial);
- What category of ED (artillery mines, grenades, etc.);
- The level of professional training of persons who manufactured and operated the ED;
- The parameter values of damaging factors of the ED, including the explosive fragment field.

Various mathematical devices and experimental methods of research are used to obtain the answers to such questions posed by the forensic expert, including trials using live ammunition. It is known that the cost of conducting such experiments is quite high, with an increased level of danger to the health and life of the expert. Further, these may be technically impossible, so methods of computer modelling are often used.

Singh[2], *et al.* has provided an estimate of the dynamic yield curve of soft steel is given under the conditions of the impact of the impact of steel bullets, and the process is simulated in a medium Autodyn 2-D using a processor Euler. Deb[3], *et al.* describes the simulation of impact of jacketed projectiles on steel armour plates using explicit finite element analysis as implemented in LS-DYNA. The newest researches on this problem elucidate a question creation of a technological device to counter the improvised explosive device[4], receipt of indexes of estimation of efficiency of the efforts directed on counteraction to the explosive devices[5] and principles of quantity distances potential explosion[6].

The use of alternative, safer methods allow forensic ballistics experts to conduct research to establish the level of danger for both military[7,8] ED and improvised explosive devices (IEDs).

This way, after analyzing and compiling an appropriate database for regular military ammunition, it will be easier to carry out the reconstruction of unknown explosive devices based on the known consequences of their explosion.

2. FORMULATION OF THE PROBLEM

The article presents the results of mathematical

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studies aimed at establishing the size of an insecure zone of fragmentation damage to the ED, namely, the spatial distribution of mass and speed of movement of two shrapnel disks of variable thickness.

3. THE MAIN MATERIAL OF THE STUDY

Within the framework of the approach developed in the work, the constituent stages of the explosion process are modeled by the following equations and relations: the deformation process of the material in the Eulerian approach is described by the Prandtl-Reis equation system; the volume compression of the metal shell is given by the theta equations; expansion of explosive detonation products is investigated according to the Jones-Wilkinson-Lee isoentropic equation[9]. The calculations were performed within the finite element method using a 450 × 800 partition grid, i.e. a total of 360000 cells, with a cell size of 0.2 mm.

The calculated schemes of the shell casing structures which were investigated are shown in Fig. 1.

All structures presented in Fig. 1 have a cylindrical body (1) with a wall thickness of 3 mm and a closed bottom. The diameter of its outer surface is 110 mm. Inside the shell body (1) is an activator (2) of blast material (BM) – an explosive mixture (RDX-40% (hexogen), TNT-30% (trinitrotoluene), Al-20%, Wax-10% (plasticizer)). The density of BM was ρ=1760 kg/m^3, the detonation velocity D=7470 m/s, the pressure at the front of the detonation wave P_{CJ}=29 GPa. At the point of contact between the end face of the BM charge and the inner bottom surface of the casing shell, the BM detonation point (4) is located on the symmetry axis.

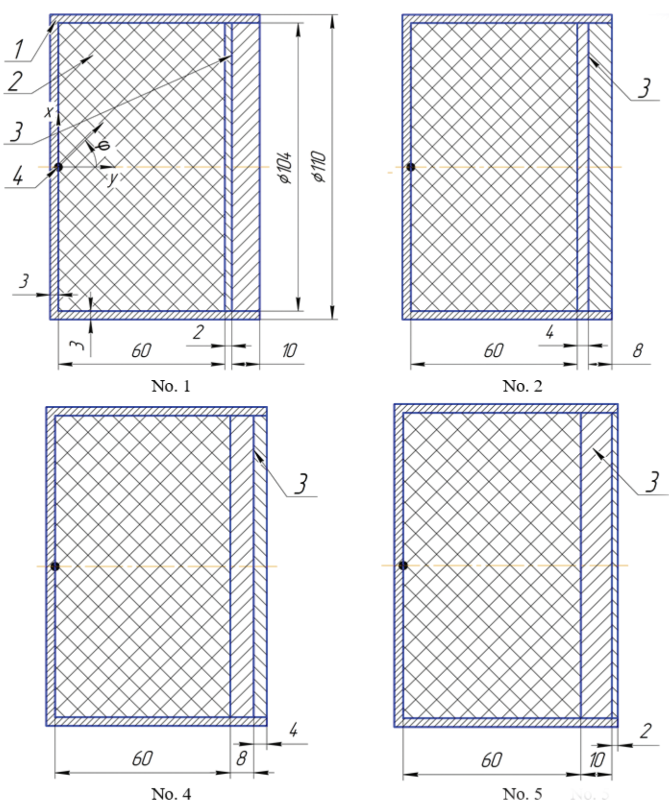

Figure 1. The calculating schemes of casing shell construction for shrapnel discs of natural crushing: No. 1, 2-10 mm; No. 2, 4-8 mm; No. 4, 8-4 mm; No. 5, 10-2 mm; 1 – frame, 2 – charge of the blast material, 3 – shrapnel discs, 4 – point action of detonation of activation on blast substance.

Scheme no. 1 (Fig. 1) with the conventional name 2-10 mm means that a disk with a thickness of 2 mm (internal disk) is located in contact with the explosive activator, followed by a 10 mm thick disk (outer disk). A similar notation is used for other schemes: scheme no. 2 (4-8 mm): internal disk – 4 mm, external – 8 mm; scheme no. 4 (8-4 mm): internal – 8mm, outer – 4 mm; scheme no. 5 (10-2 mm): inner – 10 mm, outer – 2 mm. Scheme no. 3 (6-6mm) in Fig. 1 is not presented because the process of formation of the scattering angle of the fragment mass and the velocity of its motion in a given angle was carried out in Fepa[10], *et al.*

To solve this problem, we used the method of mathematical finite element modeling using the computer program "ANSYS / LS-DYNA"[11,12]. It should be noted that the LS-DYNA is one of the most powerful software packages specially designed for the solving of essentially non-linear problems employing the method of finite elements. It is widely accepted, that at present the most successful preprocessor is the ANSYS/LS-DYNA, which, according to the geometric model, produces the finite element mesh, suitable for the elasto-plastic problems of explosion dynamics.

This program implements most of the known approaches to describing the behavior of a continuous medium under the action of impulse loading[13,14]. Considering that the solution of the problem requires a mathematical description of the behavior of both the gaseous medium (detonation products of explosive activation, air) and the solid component (metal frame shell and shrapnel disks), it is advisable to carry out computer modeling using a mixed Lagrangian-Eulerian approach[15,16] in the continuum formulation[15-17].

The three-dimensional finite element model of the problem included ¼ of the casing shell with boundary conditions superimposed on its nodes. The computer simulation of the explosion process of the shell casing (Schemes Nos. 1 and 4) is shown in Fig. 2.

In Fig. 2 it is possible to trace the main stages of the process of explosive throwing of shrapnel disks. As the detonation wave (DW) passes along the inner surface of the frame of the casing shell, it is reflected from it. As a result, a system of shock waves of compression and expansion is formed in its. At the same time, a compression shock wave is formed in the detonation products (DP) which moves in a radial direction toward the axis of symmetry.

After 9 μs from the moment of detonation of the explosive activation, the detonation wave reaches the surface of the internal disk and is reflected from it. As a result, a similar wave system is formed in the disk, as in the casing wall, and a shock wave of compression arises that moves along the axis of symmetry in the direction of the detonation initiation point 4 (Fig. 2, 12 μs). At this same time (12 μs) in the middle of the internal disk, one can see the formation of an unloading wave that moves along the axis of symmetry with a gradual expansion of its influence from the central regions of the disk to the peripheral ones.

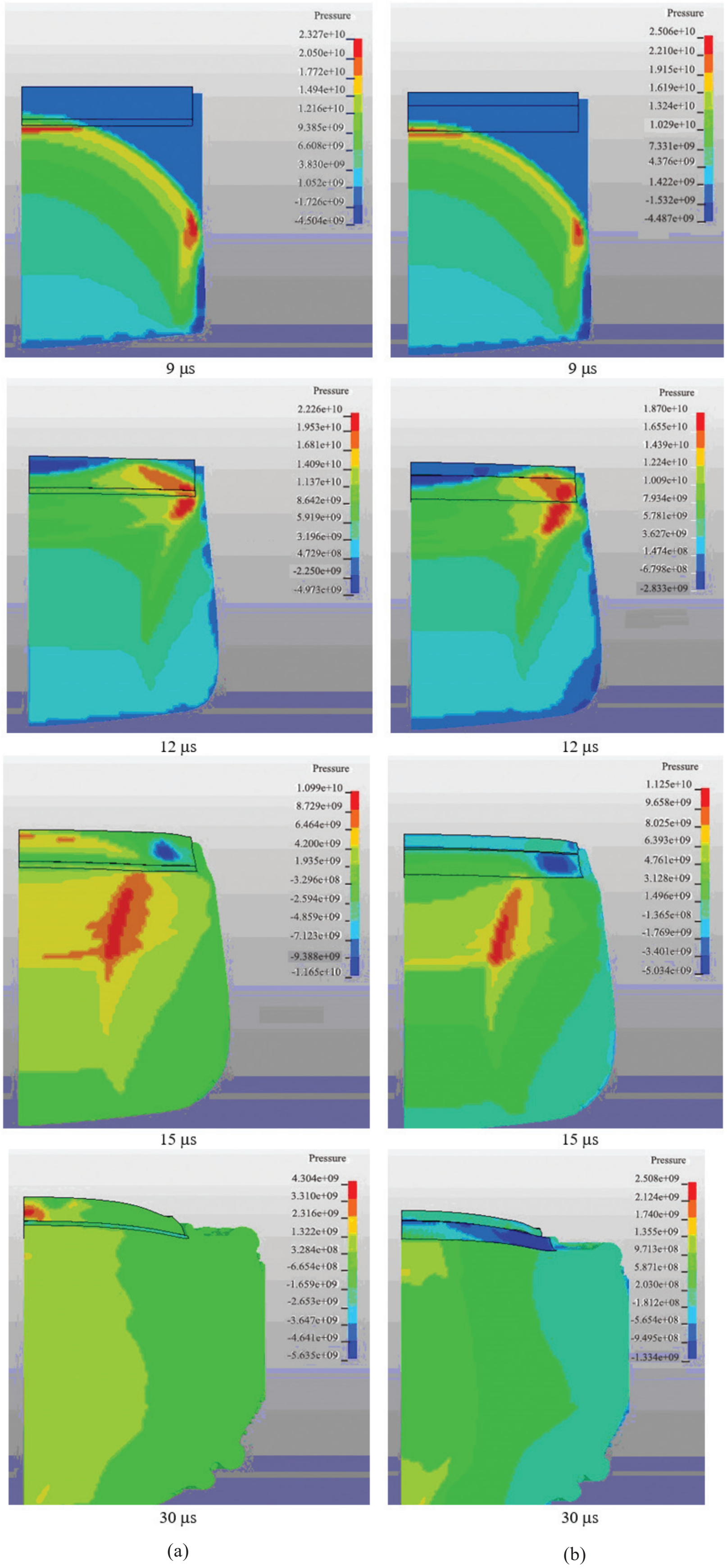

Figure 2. The frames of the computing modelling of the processes of blast throwing for two shrapnel discs: (a) scheme no. 1 and (b) scheme no. 4.

Later, the described wave energy is transmitted to disks as a certain value of the speed of motion with simultaneous deformation. At the time of 30 µs, the main wave processes terminate and, as a result, the pressure in the DP is equalised. At this moment, the process of forming the value of the total angle of expansion of the mass of shrapnel disks and its speed of motion[10] ends. However, in order to assess the Fragmentary Hazard level of the ED, the forensic expert needs information on the spatial-velocity distribution of the mass of shrapnel disks mass inside a given angle, in addition to the specified parameters. To find such a distribution, the technique[19] was used, which uses information about the change in the value of the angle of flight of the corresponding nodes of the finite-element grid of disks. The distribution of the total mass of the disks, of which the casing shell block consists, along 2° meridional angular zones, is shown in Fig. 3. The counting of the angular zones is read from the ray, which comes from the center of mass of the block and passes along its symmetry line and indicates the direction of motion of the disks.

Due to the fact that the extreme parts of the disks have large deformations, it was decided to limit ourselves to considering the behavior of casing fragments R = 45 mm. This represents a mass of 600g, or 80 % of the total mass of the shell.

Fig. 3 shows that the smallest value of the expansion angle of the fragment mass was construction scheme No. 5 with 16° of expansion. Given that all the constructions of the casing shell considered have axial symmetry, then the one shown in Fig. 3 distribution describes the motion of the mass only in one hemisphere of expansion. To determine the meridional angle of the entire structure, it is necessary to multiply the calculated values of φ by 2. Thus, the expansion of the entire mass of a thick-walled disk will be concentrated inside the expansion cone with a peak angle of 16°×2 = 32°.

From Fig. 3 it is also seen that the distribution of the mass of the disk of the scheme of shell No. 5 within a given angle is somewhat uneven. Most of its mass (23 % of 600 g) is located only in one extreme corner zone 14...16°. The transition to scheme No. 4 leads to an increase in the spreading angle to 22°, which, in recalculation for the total scattering angle, is 44°. Such an increase in the value of the angle is accompanied by a corresponding redistribution of the mass of the disks along the directions of expansion.

The data presented in Fig. 3, allow us to conclude that the first two schemes of the construction of the casing shell (No. 1 and No. 2) have approximately the same distribution of their mass along the meridional angle of expansion. In order to quantitatively compare the data obtained for the distribution of the mass of disks of all schemes of the casing shell, a mathematical processing was carried out for all angular zones of expansion and in the interval 0...16, namely,

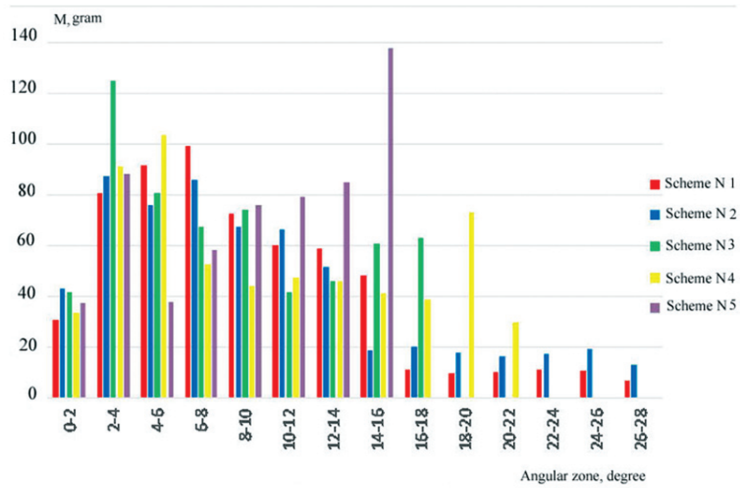

Figure 3. Distribution of the summary discs mass along meridional angle of expansion.

- Average value of the total mass of disks;
- The maximum and average deviation of the total mass of disks from the average value.

Based on the results of calculations (Table 1), it can be concluded that in the angular range of 0...16°, the most uniform distribution of the mass of shrapnel disks was scheme no. 2. In this angular range, scheme no. 2 forms the smallest value of the average deviation of the mass from the mean value.

If we consider all the angular expansion zones of future fragments, then scheme no. 2 has only the smallest value of the maximum deviation from the mean value, and the smallest average deviation from the mean value is given by scheme no. 3. At the same time, scheme no. 2 forms the smallest difference between the maximum and average deviations of the mass of disks from the mean value in the angular zones.

The mass distribution shown in Fig. 3 is integral information. To determine the reasons for the formation of these integral values, we use information on the contribution of each shrapnel disk to the mass value in a particular angular zone. The corresponding results are given in the Tables 2 and 3. In Table 3, this information was determined as the fraction (%) of the mass of the disk in the angular zone from the total mass of the disks in the casing shell to which was 600 g.

The average value is the ratio of the sum of the masses of all angular zones of the disk for the given scheme to the number of zones. For example, for the scheme no. 1 we find: 599/14 = 42.8.

The maximum deviation is the difference between the maximum value for different angular zones (column "Total" in Table 2) and the calculated average value for the given Scheme. For example for the same scheme no. 1 using the average value calculated above we obtain: 99.1-42.8 = 56.3.

To calculate the average deviation we find the sum of absolute deviations (differences) for each angular zone with respect to the average value calculated for the given Scheme

Table 1. The results of the computer simulation of average values of the total mass of the discs and his maximal and average deviation from average value

Angular zones	Parameter		Scheme number				
			1	2	3	4	5
All	Average value		42.8	42.8	66.6	54.5	74.9
	Deviation	Maximal	56.3	44.6	58.2	48.8	62.7
		Average	30.2	25.3	17.9	18.9	22.9
0-16°	Average value		67.6	61.9	67.0	57.3	74.9
	Deviation	Maximal	31.5	25.4	57.7	46.0	62.7
		Average	18.4	18.2	19.7	20.0	22.9

Table 2. The results of the computer simulation of the contribution (on gram) of shrapnel discs in common value of shrapnel mass at angle zones of expansion

Angular zone, degree	Scheme no. 1			Scheme no. 2		Scheme no. 3			Scheme no.4		Scheme no. 5		
	Disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Disc 1/2	Disc 2/2	Total
0-2	0.6	29.8	**30.4**	1.6	41.5	0.6	29.8	**30.4**	1.6	41.5	0.6	29.8	**30.4**
2-4	1.8	78.9	**80.7**	5.5	81.8	1.8	78.9	**80.7**	5.5	81.8	1.8	78.9	**80.7**
4-6	2.8	88.8	**91.6**	9.5	66.3	2.8	88.8	**91.6**	9.5	66.3	2.8	88.8	**91.6**
6-8	3.1	96.0	**99.1**	12.5	73.2	3.1	96.0	**99.1**	12.5	73.2	3.1	96.0	**99.1**
8-10	4.4	68.2	**72.7**	14.3	52.8	4.4	68.2	**72.7**	14.3	52.8	4.4	68.2	**72.7**
10-12	7.3	52.8	**60.1**	17.2	49.1	7.3	52.8	**60.1**	17.2	49.1	7.3	52.8	**60.1**
12-14	10.7	47.8	**58.5**	16.7	34.7	10.7	47.8	**58.5**	16.7	34.7	10.7	47.8	**58.5**
14-16	10.9	37.0	**48.0**	18.7		10.9	37.0	**48.0**	18.7		10.9	37.0	**48.0**
16-18	11.0		**11.0**	20.0		11.0		**11.0**	20.0		11.0		**11.0**
18-20	9.4		**9.4**	17.5		9.4		**9.4**	17.5		9.4		**9.4**
20-22	9.8		**9.8**	16.5		9.8		**9.8**	16.5		9.8		**9.8**
22-24	10.9		**10.9**	17.4		10.9		**10.9**	17.4		10.9		**10.9**
24-26	10.4		**10.4**	19.2		10.4		**10.4**	19.2		10.4		**10.4**
26-28	6.5		**6.5**	13.1		6.5		**6.5**	13.1		6.5		**6.5**
Σ	**100**	**499**	**599**	**200**	**400**	**100**	**499**	**599**	**200**	**400**	**100**	**499**	**599**

Table 3. The results of the computer simulation of the contribution (%) of shrapnel discs in common value of shrapnel mass at angle zones of expansion

Angular zone, degree	scheme no. 1			scheme no. 2			scheme no. 3			scheme no. 4			scheme no. 5		
	disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Total	Disc 1/2	Disc 2/2	Total
0-2	0.1	5.0	**5.1**	0.3	6.9	**7.2**	0.6	6.3	**6.9**	0.8	4.8	**5.6**	1.1	5.1	**6.2**
2-4	0.3	13.2	**13.5**	0.9	13.6	**14.6**	1.8	18.9	**20.8**	2.6	12.6	**15.2**	3.2	11.5	**14.7**
4-6	0.5	14.8	**15.3**	1.6	11.0	**12.6**	3.1	10.4	**13.4**	4.2	13.0	**17.2**	6.2		**6.2**
6-8	0.5	16.0	**16.5**	2.1	12.2	**14.3**	3.4	7.9	**11.2**	5.8	2.9	**8.7**	9.7		**9.7**
8-10	0.7	11.4	**12.1**	2.4	8.8	**11.2**	5.9	6.4	**12.3**	7.3		**7.3**	12.7		**12.7**
10-12	1.2	8.8	**10.0**	2.9	8.2	**11.0**	7.0		**7.0**	7.9		**7.9**	13.2		**13.2**
12-14	1.8	8.0	**9.8**	2.8	5.8	**8.6**	7.6		**7.6**	7.6		**7.6**	14.2		**14.2**
14-16	1.8	6.2	**8.0**	3.1		**3.1**	10.1		**10.1**	6.8		**6.8**	22.9		**22.9**
16-18	1.8		**1.8**	3.3		**3.3**	10.5		**10.5**	6.4		**6.4**			
18-20	1.6		**1.6**	2.9		**2.9**				12.1		**12.1**			
20-22	1.6		**1.6**	2.7		**2.7**				4.9		**4.9**			
22-24	1.8		**1.8**	2.9		**2.9**									
24-26	1.7		**1.7**	3.2		**3.2**									
26-28	1.1		**1.1**	2.2		**2.2**									
Σ	**17**	**83**	**100**	**33**	**67**	**100**	**50**	**50**	**100**	**67**	**33**	**100**	**83**	**17**	**100**

and then divide this obtained value by the number of zones. For example for the Scheme No. 1 (Table 2) we find: 452.7/14 = 30.2.

The numerical values of Table 3 in percents are obtained taking that 600 grams corresponds to 100% of the total mass of the metal shell. The values in percents presented in the Table 3 corresponding to the data (m) in grams from the Table 2 was calculated as m*100/600. For example, for the scheme no. 1 in the angular zone 0-2 degree, we find: 0.6*100/600=0.1 for the disc ½ and 29.8*100/600 = 4.96≈5.0 for the disc 2/2.

With the aim of facilitating the processing and analysis of the data of Table 2 and Table 3, the numbering of the disks was introduced. The disc that had direct contact with the explosives was assigned the number 1/2. Accordingly, the disc that was outside – 2/2.

From table 3 we can see that outer disks provide the main contribution to final mass value at the initial angular zones. At the same time, the value of their expansion angle decreases with increasing thickness of the outer disk in the case shell, from 16°, for scheme no. 1, to 4° – scheme no. 4 (which is approximately 1.3 grams/mm). A similar behavior of the value of the angle of expansion of the extreme disks was observed during studies of the explosion of a similar throwing disk in which, instead of replacing one thick-walled disk with a set of thinner disks, their number was increased[8]. In addition, the obtained dependencies of the spatial distribution of the total mass and the velocity of its motion agree well with the results obtained earlier for scheme no. 3[20].

To assess the level of danger for the action of an IED shrapnel field, in addition to the distribution of the fragment mass along the meridional angle of expansion, information was needed on the distribution of its velocity movement. The corresponding histograms for various schemes are shown in Fig. 4.

From Fig. 4 we see the distribution of the velocity of the total mass of disks along the angular zones of expansion is practically the same, if consider its distribution over a different number of angular zones. This behaviour is expected. This is due to the fact that during the replacement of one thick-walled disk with a set of thinner ones, their total mass remained unchanged.

The mass distributions and speed analysis presented in Fig. 3 and Fig. 4 allows us to assume that in order to create a narrow, high-speed, uniformly filled explosion with the mass of shrapnel disks along axial flow, it is necessary to change the geometry of the disk in such a way that most of the mass of disks is in the central angular zones 0... 2°, 2... 4 °. This should equalize the velocity of the mass of shrapnel disks along the

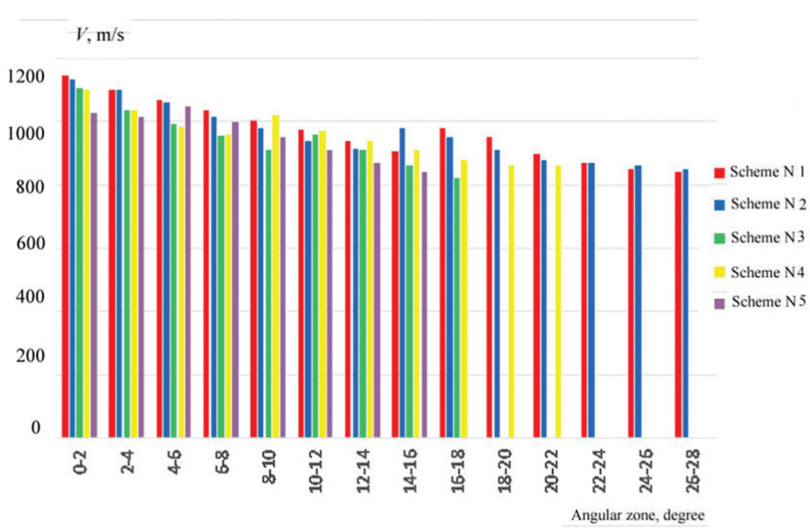

Figure 4. Distribution of velocity of the summary disc mass along meridional angle of expansion.

radius of the disks and fill the first angular zones with the required mass of fragments[21].

4. CONCLUSIONS

Based on the results of the studies, the following conclusions can be drawn:

(i) The least value of the angle of expansion of the mass of shrapnel disks is scheme no. 5 casing shell design at 16° angular zone, but the most uniform distribution of its mass inside a given angle is scheme no. 2.

(ii) The most uniform distribution of the mass of shrapnel disks over all angular zones is scheme no. 3, in which the smallest average deviation from the average value of the mass of shrapnel disks is formed.

(iii) The main contribution into the final value of the mass of shrapnel discs of natural crushing that move in the initial angular zones is carried by the outer discs of the casing shell.

(iv) The distribution of the speed of motion of the total mass of disks along the angular zones of expansion for all design circuits is almost the same.

(v) During the study of the process of explosive throwing of 10 mm thick shrapnel disks, it was established that with a threefold increased quantity, the distribution of values of total mass of expansion in the meridional angle 0...10° is practically uniform. Also, for a 2° angular zone of expansion, 125-130 g mass of disks was necessary. If such a result is recorded at the scene, then this may indicate one of the possible methods of manufacturing IEDs.

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