The relative thickness of the barriers and its fundamental importance in armored ballistics

Yu V Popov, V A Markov [1], V I Pusev, V V Selivanov

Bauman Moscow State Technical University, Moscow, Russian Federation

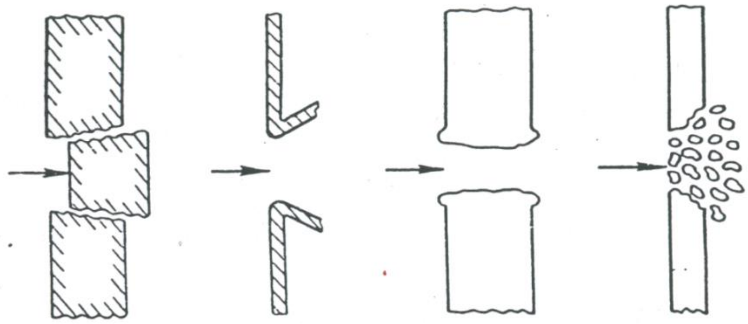
[1] markovva@bmstu.ru

Abstract. The issues of armor ballistics related to attempts to classify the types of deformation and destruction of barriers during perforation and penetration are considered. It is shown that the published classification options were not accompanied by the relative thickness of the barriers, determined by the ratio of the thickness of the barrier to the diameter of the impactor. In this regard, in some cases, the assessment of the thickness of the barriers is either humanitarian-emotional in nature, or is an erroneous quantitative assessment. Corresponding examples are given, and the classifications are supplemented by the relative thickness of the barriers. The features of evaluating the processes of perforation and penetration for caliber and sub-caliber projectiles, as well as for cumulative jets, are considered.

1. Introduction

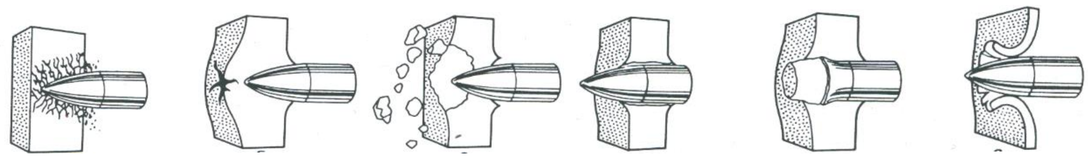
The materials of this work are an extended and in-depth version of the report [1], which for various reasons did not include specific examples of various designs of ammunition and which can confirm the main provisions of the article. The creation of screens and protective devices from the action of high-speed impactors is associated with the study of the processes of penetration and perforation (penetration is usually understood as the movement of a projectile in an barrier without leaving it, and perforation means the complete passage of the projectile through the barrier), which, along with calculation methods, are studied by virtue of their difficulties involving experimental methods [2-5].

Experimental data in a number of works are generalized and systematized [6-8]. The attempts to classify the types of deformation and destruction of barriers presented in [6, 7] (figure 1 [6], figure 2 [7]) should contribute to the development of analytical models of perforation and penetration, which cannot fully take into account the variety of physical features of processes perforation and penetration. However, they were not accompanied by the relative thickness of the barriers h/d (h is the thickness of the barrier, d is the diameter of the projectile), which depreciated their scientific and technical significance despite the full replication in [8-10]. In [8, 10], the classification of the destruction of barriers [7] was supplemented by their division by thickness into thin, medium (intermediate thickness [8]), thick and semi-infinite. According to [8], in thin obstructions, stresses and strains are constant in thickness, in medium obstructions, the rear surface of the obstruction has an effect on almost the entire process of movement of the projectile, in thick obstructions, the rear surface of the obstruction has a partial effect after a considerable distance, and in semi-infinite back surfaces does not affect the penetration process. In [10], it is indicated that the separation of barriers by thickness should be carried out with respect to the diameter of the impactor, but without specifying the relative thicknesses h/d for each type of fracture. The only classification for barrier destruction, supplemented by relative thicknesses, is contained in [11].



(a) (b) (c) (d)

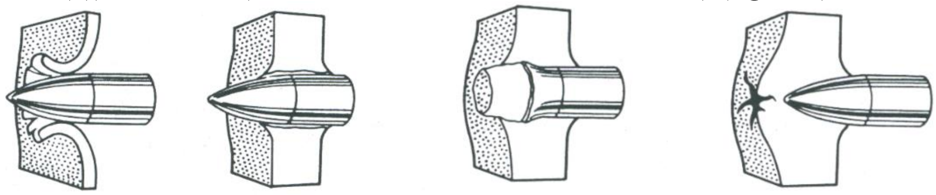
Figure 1. Classification of types of deformation and destruction of barriers: (a) – "cork" formation; (b) – the formation of fringes; (c) – malleable expansion of the hole; (d) – spallation. Figure reprinted from [6].



(a) (b) (c) (d) (e) (f)

Figure 2. Classification of types of deformation and destruction of barriers: (a) – brittle fracture; (b) – fracture with the formation of radial cracks; (c) – crushing; (d) – plastic expansion of the hole; (e) – knocking out the cork; (f) – formation of petals. Figure reprinted from [7].

As a result, in [6], a review of works [12, 13] on breaking through relatively thin plates corresponds to the primary sources, and in [8] the same works are unreasonably opposed. In this paper, based on an analysis of experimental and calculated data and taking into account the results of [11], the classification of the types of perforation of metal plates [7-10] is supplemented by relative thicknesses as follows: thin plates (figure 3 (a)) – h/d <0.5 (formation of petals; field of application of the theory of thin shells [14]); average barriers (figure 3 (b), (c)) – 0.5 <h/d <1.5 (plastic expansion of a hole or knocking of a stopper; field of application of the Jacob de Marr formula [8]); thick and semi-infinite barriers (figure 3 (d)) – h/d> 1,5 (formation of radial cracks and fracture) (figure 3).



(a) (b) (c) (d)

Figure 3. Classification of types of penetration of metal barriers. Figure reprinted from [7].

2. Features of the processes of perforation and penetration into metal plates, taking into account the relative thickness of the barrier

The absence of such assessments has led to statements in the literature that "very thin plates are rarely used when armor" [8], and in [10] the field of application of thin plates is limited only by elements of dynamic protection of tanks and elements of protection of spacecraft. Moreover, the measure of "subtlety" and "very subtlety" is not indicated in [8, 10], which makes it possible to attribute such assessments to humanitarian and emotional ones that do not represent engineering and technical value. Moreover, these statements from [8, 10] are erroneous. Based on studies conducted in [15-18], it was established that the practice of armor combat surface ships of the world does not confirm the statement of work [4]. Even the American system of armor battleships, called “all or nothing”, focused on the concentration of armor only in the citadel, did not go out of the thin plate area in horizontal armor ($h/d < 0.5$) and partially fell into the region of very thin plates ($h/d < 0.1$) with respect to the main caliber of their own artillery (d) [17]. As for [8], this publication by an employee of the US Army Ballistic Research Laboratory was exactly what the representative of the “ground” could do (in the terminology of [19]) units operated by the army, not the navy.

In general, the arbitrariness in the assessment of thin plates, mentioned as existing on the humanitarian and emotional level, is also manifested at the level of quantitative assessments. In almost the same authors, plates with a relative thickness h/d = 0.5 [11] are assigned to thin bulletproof armor and the petal mechanism of hole formation is associated with it, and in [20] plates with h/d = 1.17, and the petal mechanism of the hole is connected with the plate with h/d <0.58 [20], but in [21] plates with h/d <1 and without the petal mechanism of formation of the hole are classified as thin plates. For thin bulletproof armor, the range of the relative thickness of the plate h/d <0.8 is indicated in [22], and the record given in [23], where plates with a relative thickness during normal impact are classified as thin bulletproof armor, are indicated in the range h/d = 0.61 … 1.13, which, at approach angles of the projectile 70º … 80º from the normal (NATO angle [23]), is transformed into the range h/d = 1.78 … 3, 3 (angle 70º from the normal) or in the range h/d = 3.5 … 6.5 (angle 80º from the normal). As they say, no comment.

In fact, for the first time in the world, the problem of breaking through armor with a thickness of less than half a caliber of a projectile (h/d <0.5) or low resistance targets [24] has been dealt with in Russia since 1900 in connection with the development of a bottom tube, and subsequently a fuse [16-18, 24] for armor-piercing and deck-piercing shells of naval and coastal artillery [24]. These developments were carried out by Andrei Andreyevich Dzerzhkovich (1875-1934 [25]), a graduate of the 1900 Mikhailovsky Artillery Academy [18]. Abroad, research in the field of perforation of thin plates began only in 1940 during the Second World War in connection with the development of a fuse for anti-aircraft shells in the UK [26]. Analytical dependences were obtained for calculating the energy needed to break through a thin plate, the calculation results for which were very far from the experiment in the ballistic limit region [27], and in cases of exceeding the ballistic limit they gave satisfactory results [6]. The use of numerical modeling based on the theory of thin shells significantly increases the accuracy of calculating the ballistic limit when a cylinder projectile a normal along a thin plate. In addition, satisfactory information can be obtained on the deformation of the plate and the forces acting on the projectile during deformation [14, 27].

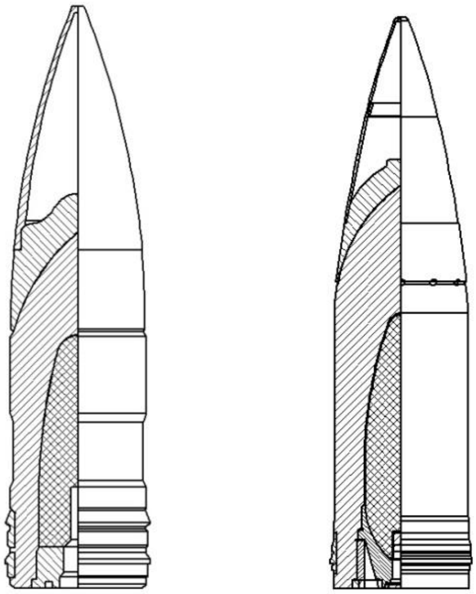
It should be noted that in pre-revolutionary Russia and the USSR, due to a number of circumstances, the Jacob de Marr formula was widely used to calculate the perforation of medium-thick armor. However, in [28], 10 empirical formulas of various manufacturers of armor and authors are given: for homogeneous armor, Feinburn (Great Britain, 1870s), Tressider (Great Britain, until 1870), Krupp (Germany, until 1870) , Jacob de Marr (France, later 1870), Le Havre (France, 1870); for heterogeneous armor and shell with armor-piercing tip – Krupp (Germany, 1895), Davis (USA, 1900); universal formulas – Jacob de Marr (1895), Krupp (Germany, 1930). The listed formulas can be reduced to the following generalized formula [18, 28]:

$$\frac{h}{d} = Ad^B \left[\left(\frac{P}{d^3}\right)\left(\frac{V}{C^D}\right)^E \right]^F \tag{1}$$

where P, V – mass and speed of ammunition; A, B, C, D, E, F are empirical constants.

In formula (1), gauge d and obstacle thickness h are specified in inches (0.0254 m), mass in pounds (0.45359237 kg), and speed in feet per second (foot – 0.3048 m) [18, 28].

The results of the calculation according to the formulas for shells with armor-piercing tips (figure 4 [29, 30]) by Davis (USA, 1900) and Krupp factories (Germany, 1930) showed the advantage of the German armor-piercing shell of the Bismarck battleship in comparison with the English the cruiser Hood [29, 30] in terms of relative thickness of penetrated armor *h/d* 1.26…1.34 versus 0.996…1.02 (table 1). This calculation result coincides with the estimates of [31]. It should be noted the relatively significant content of explosives in the design of anti-ship armor-piercing shells.



(a) (b)

Figure 4. Armor-piercing shells with armor-piercing tips of World War II: (a) – German projectile for the gun 38 cm/52 (14.96") SK C/34; (b) – English projectile for the gun 15"/42 (38.1 cm) Mark 1. Figure reprinted from [29, 30].

Table 1. Ultimate relative thickness of penetrated heterogeneous armor for German and British armor-piercing shells of caliber 380/381 mm.

Formula Name	Empirical Constants						*h/d*	
	A	*B*	*C*	*D*	*E*	*F*	Germ.	Brit.
Davis (USA, 1900)	0.00008582	0.25	1	0	2	0.625	1.26	0.996
Krupp (Germany, 1930)	0.30386	0.25	658…663	1	2	0.625	1.34	1.02

It should be noted that the largest artillery armor-piercing shell of World War II was the Japanese 460-mm type 91 [32]. It should be borne in mind that the given classification (figure 3) is associated with caliber projectiles and is based on the "artillery approach", when the thickness of the perforated barrier or the depth of the cavity during penetration can be measured in diameters of the projectile, which coincides with the internal diameter (caliber) of the barrel of the ballistic installation. A similar approach would be unphysical for sub-caliber projectiles.

It is known [33] that the considered gauge armor-piercing shells could penetrate armor with a relative thickness *h/d* = 1.2 … 1.3, and subcaliber with a relative thickness *h/d* = 2 … 3. However, only the armor-piercing core participated in the penetration of the barrier, the diameter of which for sub-caliber shells with an inseparable tray of reel or streamlined shape was $d_c = 0{,}4d$ (figure 5) [34].

Then, in the core diameters, the relative thickness of the penetrated barrier will $h/_{d_c}$ = 5…7 [33, 34]. In modern armor-piercing subcaliber projectiles with a detachable pallet, the relative thickness of the penetrated barrier can reach $h/_{d_c}$ = 20 or more [35].

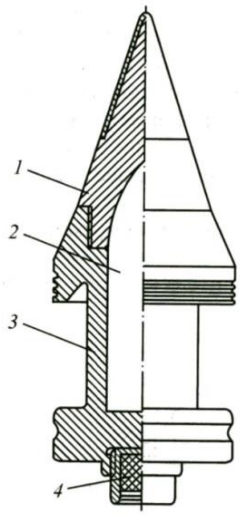


Figure 5. Armor-piercing projectile with a reel-shaped pallet: *1* - ballistic tip; *2* - armor-piercing core; *3* - pallet: *4* - tracer. Figure reprinted from [34].

A similar situation is typical for evaluating the results of perforation or penetration of shock nuclei or cumulative jets. So, for modern shaped-charge shells and aerial bombs (figure 6) [34], the range of relative thicknesses of barriers with the "artillery approach" is *h/d* = 3.6…4.0 [34]. If we assume that the diameter of the cumulative jet is $d_c = 0{,}05d$, then the indicated range of penetrated thicknesses can be counted, and it will be $h/_{d_c}$ = 73…80.

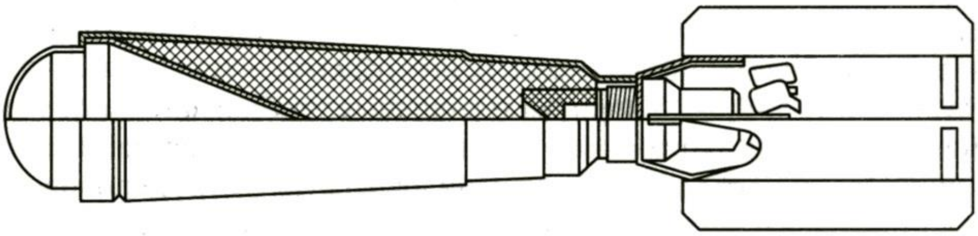


Figure 6. Experimental anti-tank bomb PTAB-10-2.5 model 1944 using cumulative action. Figure reprinted from [34].

3. Conclusion

1. The questions of armor ballistics related to attempts to classify the types of deformation and destruction of barriers during perforation and penetration are considered.

2. Based on the analysis of experimental and calculated data, the existing classification of the types of penetration of metal plates: thin plates – *h/d* <0.5 (formation of petals; field of application of the theory of thin shells); average barriers – 0.5 <*h/d* <1.5 (plastic expansion of a hole or knocking of a stopper; field of application of the Jacob de Marr formula); thick and semi-infinite barriers – *h/d*> 1,5 (formation of radial cracks and fracture).

3. The features of evaluating the processes of perforation and penetration for caliber and sub-caliber projectiles, as well as for cumulative jets, are considered.

4. Thus, the relative thickness of the barrier to be pierced is the most important and even fundamental characteristic of armored ballistics, and its correct application avoids not only errors, but also armor fears.

4. Acknowledgment
This work was partially supported by the Russian Foundation for Basic Research (project No. 19-08-00701-a).

Notations

38 cm / 52 (14.96 ”) SK C / 34 - German cannon
15 ”/ 42 (38.1 cm) Mark 1 - English cannon
PTAB-10-2.5 - Soviet experimental anti-tank bomb

References
[1] Markov V A, Ovchinnikov A F and Pusev V I 2015 *Proc. of the International conference 17th Khariton Readings* (Sarov: Russian Federal Nuclear Center - All-Russian Research Institute of Experimental Physics Publ.) p 572
[2] *Teoreticheskiye i eksperimental'nyye issledovaniya vysokoskorostnogo vzaimodeystviya tel*, edited by A Gerasimov 2007 (Tomsk: Tomsk State University Press) p 572
[3] Fomin V, Gulidov A, Sapozhnikov G et al 1999 *High-speed interaction of bodies* (Novosibirsk: Publishing House of the Siberian Branch of the Russian Academy of Sciences) p 600
[4] Hazell P 2016 *Armour: Materials, Theory and Design* (Publisher: CRC Press) p 395
[5] Ben-Dor G, Dubinsky A and Evperin T 2019 *Engineering model in high speed penetration mechanics and their applications* (World scientific) p 1116
[6] Goldsmith W 1960 *Impact* (London: Arnold) p 448
[7] Backman M E and Goldsmith W 1978 *Int. J. Engng. Sci.* **16** 2
[8] Zukas J A 1982 Penetration and Perforation of Solids *Impact Dynamics* (New York: Wiley) pp 155-214.
[9] Sagomonyan A Ya 1988 *The dynamics of breaking through barriers* (Moscow: Moscow State University Pres) p 160
[10] Balagansky I A, Merzhievsky L A 2004 *The effect of weapons and ammunition* (Novosibirsk: Publishing House NSTU) p 408
[11] Letnikov A Yu, Kobylkin I F, Kulakov I V 1998 *Double technology* **2** 76
[12] Thomson W 1956 An approximate theory of penetration of armor *Mechanics (collection of translations)* **1** 134
[13] Zaid M, Paul B 1957 *J. Franclin. Inst.* **264-2** 117
[14] Pusev V I 2003 *IX International Symposium "Dynamic and Technological Problems of Mechanics of Structures and Continuous Media"* (Moscow: MAI Pres) p 40
[15] Pusev V I, Ovchinnikov A F, Markov V A, Kiselev V M and Andryushin A A 2007 *Defence technology* **3-4** 104
[16] Pusev V I, Ovchinnikov A F, Markov V A, Kiselev V M and Andryushin A A 2009 *Defence technology* **1-2** 53
[17] Pusev V I, Ovchinnikov A F, Markov V A, Kiselev V M and Andryushin A A 2010 *Defence technology* **2-3** 98
[18] Pusev V I, Ovchinnikov A F, Markov V A, Kiselev V M and Kupriyanov V M 2011 *Defence technology* **2-3** 94
[19] Kuzin V P, Nikolsky V I 1996 *The navy of the USSR 1945-1991* (St. Petersburg: Historical Maritime Society) p 653
[20] Grigoryan V A, Kobylkin I F, Marinin V M, Chistyakov E N 2008 *Materials and protective structures for local and individual reservations* (Moscow: RadioSoft) p 406

[21] Kobylkin I F, Selivanov V V 2014 *Materials and structure of light armor protection* (Moscow: BMSTU Pres) p 191
[22] Ageev N P, Ignatenko V V, Bogatov S N 2008 *All-Russian Scientific and Technical Conference "Fundamentals of Ballistic Design"* (St. Petersburg: BSTU named after D.F.Ustinova) p 36
[23] Yaziv D, Mayseless M, Reifen Y 2001 *Proc. 19-th Int. Symp on Ballistics* (Interlaken Switherland) p 1249
[24] Rdultovsky V I 1940 The historical outline of the development of tubes and fuses from the beginning of their use to the end of the world war of 1914-1918 (Moscow: Oborongiz) p 240
[25] Ladov S V 2013 *Department of "High-Precision Airborne Devices" BMSTU. People, events, development history. 1938-2013* (Moscow: Publishing House of BMSTU) p 422
[26] Zaid A I O, El-Kalay A, Travis F W 1973 *Int. J. Mech. Sci.* **15-2** 129
[27] Pusev V I 2002 *Defence technology* **1-2** 80
[28] Okun N *Major historical naval armor penetration formulae 26.11.2001* URL: http://www.navweaps.com/index_natan/Hstfmla.htm
[29] *Naval weapons, naval technology and naval reunions*. URL: http://www.navweaps.com/weapons/index_weapons.htm
[30] *Armor-piercing shot and shell* URL: http:// en.wikipedia.org /wiki /Armor_piercing_shot_and_shell
[31] Balakin S A, Dashyan A V, Potyanin S V, Tokarev M Yu and Chausov V N 2006 *Battleships of World War II: the Attack Force of the Fleet* (Moscow: Collection, Yauza, Eksmo) p 255
[32] Kofman V L 2006 *Japanese battleships of the Second World “Yamato” and “Musashi”* (Moscow: Collection, Yauza, Eksmo) p 128
[33] Latukhin N A 1970 *Modern artillery* (Moscow: Military Publishing) p 320
[34] Babkin A V, Veldanov V A, Gryaznov E F et al 2008 *Means of destruction and ammunition* (Moscow: Publishing House BMSTU) p 984
[35] Grigoryan V A, Beloborodko A N, Dorohov N S et al 2006 *Particular questions of finite ballistics* (Moscow: Publishing House BMSTU) p 592