

Deformation and fracture behavior of steel projectiles impacting AD95 ceramic targets-experimental investigation

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Abstract. The deformation and failure behaviors of soft and hard steel projectiles and ceramic targets during normal impact at different velocities were investigated experimentally. Impact tests were conducted with light gas guns over a range of velocities from 100 to 1000 m/s. The projectile and target, including fragments, were recovered after each test. Experimental results show that, with the impact velocity increasing, for the soft projectiles, the deformation and fracture modes were mushrooming, shear cracking, petaling and fragmentation (with relatively large fragments and lower number), respectively, while for the hard projectiles there are three deformation and fracture modes: mushrooming, shearing cracking and fragmentation (with very small fragments and large number). Velocity ranges were identified for each failure mode. In all tests, projectiles were rebounded and did not fully penetrate the ceramic targets. However, as a function of the velocity, the failure mode of ceramic target changed. At low impact velocity, only radial cracks formed. As impact velocity increased, circumferential cracks could be seen. A conical region of was ejected from the rear of the ceramic target when the velocity reached 400 m/s or above. The portion of the target affected by the conical ejected region took on two separate forms: front surface intact at lower velocity and perforated at higher velocity. At the higher impact velocities, the fragment size in the ceramic cone is smaller and more of a uniform distribution. No obvious difference in the damage to the ceramic target is seen with projectiles having different hardness but impacting at the same velocity range.

1. Introduction

Penetration- and impact-related problems have been studied for a long time in order to describe the phenomena occurring in abrupt collision problems. Ceramics, as high hardness and low density materials, have been widely used as armor materials in tanks, armored vehicles, etc. Many investigations have studied impact and penetration by metal projectiles, such as steel or tungsten alloy, into semi-infinite thickness ceramic targets or ceramic/metal combination targets [1-9]. Most of the relevant research has been concerned with the backing plate depth of penetration, ceramic failure mode, resistance to penetration and failure behavior of layered structures. However, less attention has been paid to the deformation and fracture modes of projectiles after impacting finite thickness ceramic

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This work is supported by National Nature Science Foundation of China under Grant 11072072.



targets without any backing plates. Meanwhile, the relationship between ceramic failure and projectile deformation and fracture is also an interesting topic of research.

In this study, the deformation and failure behavior of projectiles and ceramic targets in normal impacts was investigated experimentally. A series of normal impact tests into AD95 ceramic targets were conducted using steel projectiles having two different hardness, at impact velocities ranging from 100 to 1000 m/s. The projectile and target, including fragments, were recovered after each test.

2. Experiment set-up

A two-stage compressed gas gun test facility, with 57 mm diameter pump tube and 7.62 mm diameter launch tube, installed at the Hypervelocity Impact Research Center in Harbin Institute of Technology, was used to conduct most of the impact tests. The lowest velocity tests were conducted using a one-stage gas gun with 7.62 mm diameter.

Cylindrical projectiles 7.6 mm in diameter and 22.8 mm in length, with the average mass 7.95 g, were used in the tests. Projectiles were manufactured using 38CrSi steel with two different heat treatments to produce two different hardness states. One set of projectiles, designated S-B, had a Rockwell hardness of 19.3HRC, while the second set, designated H-B, had a Rockwell hardness of 55.1HRC. The material parameters of the projectiles can be found in reference [10].

The targets were AD95 ceramic discs 84 mm in diameter and 20 mm in thickness. The AD95 alumina ceramic is made up of 94.5% Al_2O_3 , 1.5% SiO_2 , 3% CaCO_3 and small amounts of viscose, and produced by hot-press sintering, with the average density of 3741 kg/m^3 . The detailed material parameters of the target can be found in reference [11].

The ceramic target was constrained by two cover rings and a hoop, without any backing plate. The inside and outside diameters of the cover rings were 70 mm and 120 mm, respectively, and the thickness was 3.2 mm. The inside diameter and thickness of the hoop are same with the ceramic target and the outside diameter was same as the cover rings. The assembled target was installed in a target holder, as shown in figure 1. Figure 2 shows the target components and an assembled target, as well as the projectile dimensions.

The faces of the ceramic targets were colored blue to improve the ability to see fractures after the tests. Transparent tape was placed on the two surfaces of the ceramic target to facilitate post-shot recovery.

The impact process was recorded and the projectile velocity was obtained by a high-speed video camera. Figure 3 shows images from a typical impact test.

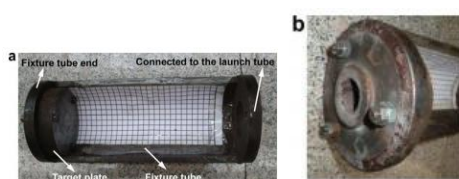


Figure 1. Target installation. (a) Global view. (b) Back view of the rear side of the fixture tube end.



Figure 2. Target system and projectile. (a) cover ring; (b) hoop outside the ceramic target; (c) ceramic target (d) projectile shape and size.

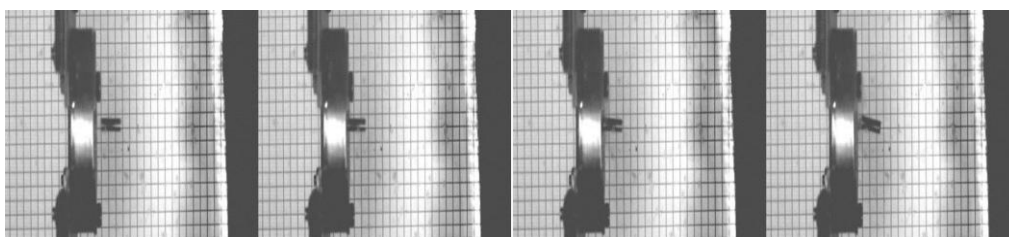


Figure 3. Typical impact process pictures by high-speed camera (H-B, $v=162.3 \text{ m/s}$).

3. Experimental results

A total of 25 experiments were conducted over a range of velocities from 100 to 1000 m/s, including 14 with H-B projectiles and 11 S-B projectiles. For all tests, projectiles were observed to rebound and did not pass through the ceramic targets. Several deformation and fracture modes of the projectiles and targets were identified during examination of the recovered projectiles and targets. Table 1 shows the detailed information of the recovered projectiles and targets, where v_i , m_{r-p} , L_{r-p} , D_{r-nose} , D_{cone} and N_{cracks} denote initial velocity of projectile, mass of residual projectile, length of residual projectile, diameter of residual projectile nose, bottom diameter of ceramic cone and the number of cracks on front ceramic surface. The cone angle is defined as shown in figure 4.

Sieve analysis results of the ejected target materials are shown in table 2, where two kinds of sieves mm with 5 mm hole and 10 mm hole, respectively. In table 2, m_{cone} , m_f and N_f denote mass of ceramic cone, mass of ceramic fragments in a particular size range and fragment number in the range of size > 10 mm.

Table1. The detailed information of the recovered projectiles and targets.

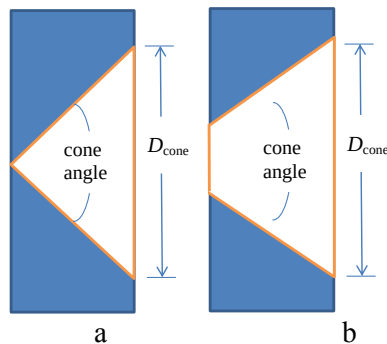
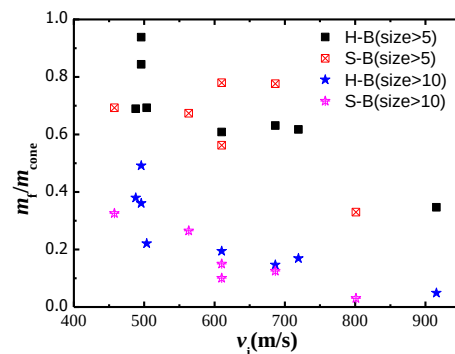
#	v_i / (m/s)	m_{r-p} / (g)	L_{r-p} / (mm)	D_{r-nose} / (mm)	Status-p	D_{cone} / (mm)	cone angle/°	N_{cracks}
H-B-1	126.8	7.90	22.63	8.1	Mushrooming	--	--	6
H-B-2	138.9	8.01	22.74	8.3	Mushrooming	--	--	5
H-B-3	161.3	7.91	22.22	8.81	Mushrooming	--	--	9
H-B-4	162.0	7.95	22.5	8.4	Mushrooming	--	--	7
H-B-5	174.7	7.94	22.19	8.76	Mushrooming	--	--	9
H-B-6	200.6	7.92	21.85	9.3	Mushrooming	--	--	9
H-B-7	488.1	4.99	15.8	--	Fragmentation	68	119.1	6
H-B-8	495.9	4.83	14.5	--	Fragmentation	67	118.3	5
H-B-9	495.9	4.59	14.5	--	Fragmentation	64	116	6
H-B-10	503.5	4.54	14.17	--	Fragmentation	55	108	6
H-B-11	610.3	3.75	12.25	--	Fragmentation	68	100.4	--
H-B-12	686.6	3.58	11.1	--	Fragmentation	66	98	--
H-B-13	719.3	3.15	10	--	Fragmentation	69	91.5	--
H-B-14	915.5	4.06	13.6	--	Fragmentation	66	119.3	--
S-B-1	125.8	7.99	22.36	8.3	Mushrooming	--	--	0
S-B-2	135.4	7.96	22.13	8.2	Mushrooming	--	--	6
S-B-3	143.0	8.01	22.3	8.6	Mushrooming	--	--	3
S-B-4	162.0	7.97	21.77	8.9	Mushrooming	--	--	6
S-B-5	208.3	7.95	21.02	9.77	Mushrooming	--	--	8
S-B-6	457.7	6.00	13.5	--	Petaling	60	112.6	5
S-B-7	563.4	3.82	10.7	--	Petaling(detaching)	68	119.1	8
S-B-8	610.3	5.14	9.44	--	Petaling(detaching partly)	68	100.4	--
S-B-9	610.3	4.60	10	--	Petaling(detaching partly)	64	116	7
S-B-10	686.6	2.92	8.12	--	Fragmentation(detaching)	69	119.8	6
S-B-11	801.1	3.78	10.2	--	Fragmentation(detaching)	69	84	--

Table2. The detailed information of the recovered projectiles and targets.

#	v_i / (m/s)	$m_{\text{cone}}/$ (g)	m_f (g) (size>5)	m_f (g) (size>10)	N_f (size>10)	m_f (g) (5≤size<10)	Status-front surface
H-B-7	488.1	90.5	62.4	34.35	8	28.05	Intact
H-B-8	495.9	87.9	74.17	31.68	10	42.49	Intact
H-B-9	495.9	80.2	75.25	39.43	8	35.82	Intact
H-B-10	503.5	59.2	41	13.07	5	28.03	Intact
H-B-11	610.3	125.0	76.08	24.32	6	51.76	Non-intact
H-B-12	686.6	119.0	75.1	17.45	6	57.65	Non-intact
H-B-13	719.3	119.3	73.65	20.15	5	53.14	Non-intact
H-B-14	915.5	92.6	32.08	4.5	2	27.58	Non-intact
S-B-6	457.7	70.5	48.83	22.96	6	25.37	Intact
S-B-7	563.4	90.5	60.98	24	10	36.98	Intact
S-B-8	610.3	80.2	62.52	12.02	5	50.5	Non-Intact
S-B-9	610.3	117.5	66.11	11.83	4	54.28	Intact
S-B-10	686.6	93.2	72.36	11.7	4	60.66	Intact
S-B-11	801.1	159.1	52.44	4.87	2	47.57	Non-Intact

Figure 5 shows the relationship of mass distribution and velocity in different fragment size ranges.

The deformation and fracture modes of projectile and target were identified with specific velocity ranges, as discussed below.

**Figure 4.** Schematic of ceramic cone. (a. front surface intact; b. front surface non-intact)**Figure 5.** The relationship of mass distribution and velocity in different fragment size ranges.

3.1 $v < 210$ m/s

Figures 6 and 7 show typical deformation and fracture modes of the H-B and S-B projectiles, as well as the targets, at low velocity. The projectiles mushroom for both hardnesses of projectile, but with greater deformation for the S-B projectiles. The targets remain largely intact, with only radial cracks visible on front and rear surfaces.

3.2 $400 \text{ m/s} < v < 600 \text{ m/s}$

Figures 8 and 9 show typical results from tests in the 400-600 m/s range for H-B and S-B projectile impacts, respectively. In both tests, a conical region was ejected from the rear surfaces of targets, but the front surfaces were basically intact, with radial and circumferential cracks. The H-B projectile forward portion fragmented, while the S-B projectile continued to display mushrooming behavior,

with tears in the expanded region leading to a “petaling” effect, with a few of the petals detaching from the projectile.



Figure 6. Deformation and fracture modes of H-B projectile and target at velocity 161.3 m/s.

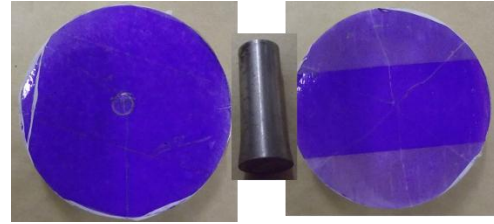


Figure 7. Deformation and fracture modes of S-B projectile and target at velocity 162.0 m/s.

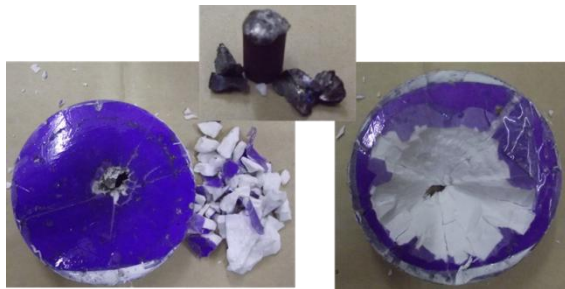


Figure 8. Deformation and fracture modes of H-B projectile and target at velocity 503.5 m/s.

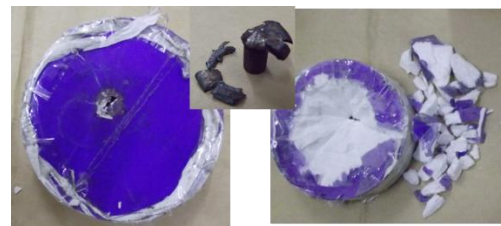


Figure 9. Deformation and fracture modes of S-B projectile and target at velocity 457.7 m/s.

3.3 $600 \text{ m/s} < v < 700 \text{ m/s}$

In the 600-700 m/s speed range, impact by the H-B projectile produces a large hole on the target front surface. For impact by the S-B, the target front surface remains intact, with the exception for the fractures noted at lower velocities. The conical region ejected from the rear surface is similar to that observed in the 400-600 m/s range. The fracture modes of the two kinds of projectiles are also similar to those observed in the 400-600 m/s velocity range. The primary difference is more fragmentation at the higher velocities. Figures 10 and 11 show the typical deformation and fracture modes of projectiles and targets in this velocity range.



Figure 10. Deformation and fracture modes H-B projectile and target at velocity 610.3 m/s.



Figure 11. Deformation and fracture modes S-B projectile and target at velocity 610.3 m/s.

3.4 $v > 700 \text{ m/s}$

At impact velocities greater than 700 m/s, for the two kinds of projectiles, the conical void in the rear of the target is similar to those at lower velocities and the front surfaces are penetrated by large holes, with significant fragmentation of the target outside the conical ejecta region. If the target is not covered by tape, as described earlier, it can fall into a set of large fragments. For the both the H-B and S-B projectile types, the intact rear portion of the projectile is very short compared to the original projectile length. The fragmented portions of the projectiles are characterized by a smaller number of relatively larger fragments for the S-B projectiles as compared to the H-B projectiles. Figures 12 and 13 show the typical deformation and fracture modes of the projectiles and targets in this velocity range. At higher velocity, the ceramic fragments are smaller and size is more uniform.



Figure 12 Deformation and fracture modes H-B projectile and target at velocity 915.5 m/s.



Figure 13. Deformation and fracture modes S-B projectile and target at velocity 801.1 m/s.

Conclusion

Experimental results show that, with the increasing impact velocity into ceramic targets, for soft steel projectiles, the deformation and fracture modes progress from mushrooming through petaling to shear cracking and fragmentation, while for hard steel projectiles the progression is from mushrooming to shear cracking and fragmentation. For all tests, projectiles rebounded and did not penetrate through the ceramic targets.

At low impact velocities, only radial cracks were observed in the ceramic target progressing to include circumferential cracks with increasing velocity, while a conical region was ejected from the rear of the target at impact velocities above 400 m/s. The resulting conical void did not breach the impact surface of the target at lower velocities, but did at higher velocities, with formation of a large hole in the front surface of the target. At higher impact velocity, the fragment size in the ejected material is smaller with a more uniform distribution. No obvious difference in damage was observed between ceramic targets impacted by the two different hardnesses of projectile.

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