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Technical Report

Effect of projectile hardness on deformation and fracture behavior in the Taylor impact test

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ABSTRACT

The ballistic perforation performance of a kinetic energy projectile would be much more influenced by the projectile's deformation during the impact process. A projectile may suffer from large deformation and even fracture as more and more advanced materials are used as resistant components. A comparison investigation was presented in this study concerning the deformation and fracture behavior of kinetic energy projectiles manufactured from 38CrSi steel of two different hardness values. Flat-nosed projectiles were fired in a two-stage compressed gun test facility against hard steel plates within the velocity range of 200–600 m/s. The impact process was monitored by a high-speed camera. Experimental results showed that, for the soft projectiles there are three deformation and fracture modes, i.e., mushrooming, shear cracking and petalling, and that for the hard projectiles there are also three modes, mushrooming, shearing cracking and fragmentation.

1. Introduction

A missile can be either hard and relatively undeformable or ductile and very deformable in comparison with a target plate. It changes shape as it penetrates a target. In fact, normal impact of a projectile at sufficiently high velocity often results in not only plastic deformation but also possibly fracture in the penetrating projectile itself, even against soft targets. For example, Børvik et al. [1] experimentally found that 20 mm diameter blunt projectiles can be completely shattered in penetration of 20 and 30 mm thick Weldox 460 E steel plates. Similar phenomena can also be found in Refs. [2,3]. The deformation and possible fracture would greatly influence the final impact performance. Investigations on the deformation and fracture of a kinetic energy projectile can advise warhead design. A survey of previous literature shows that lots of research interests on impacts at sub-ordnance and ordnance impact velocities focused on the penetration and perforation caused by rigid projectiles (see Børvik et al. [4], Teng et al. [5], Gupta et al. [6], etc.), and that few papers dealt with deformation in an impacting projectile itself, especially fracture. It is interesting to note that the deformation and fracture characteristics of a projectile can be approximately obtained by Taylor impact test (Taylor [7,8] and Whiffin [9]), which involves the normal impact of a cylindrical rod onto a stationary, large, rigid, and smooth-faced anvil. Regarding Taylor impact test, over 400 papers have been published over the past 50 years [10]. However, most of the papers deal with dynamic yield stresses and material constitutive models, and very limited studies concentrate on deformation and fracture.

Woodward et al. [11] performed Taylor tests on steel rods, and showed several pictures illustrating both tensile splitting and fragmentation. Couque [12] observed several 45° shear cracks on the lateral surface of both the projectile and target cylinders in the symmetric Taylor test (Critescu and Bell [13]). Chapman et al. [14] reported the Taylor impact tests on projectiles of aluminum alloy Al-6082-T6. They observed not only petalling in both the classic and symmetric Taylor test, but also void nucleation in the central axis of both the projectile and target rods in some symmetric Taylor impact tests. However, it should be noted that the petalling herein seems to be caused by shear cracking (the pictures illustrating the fractured projectiles clearly showed 45° shear cracks). By numerical simulations, Teng et al. [15] found three distinct fracture modes: confined fracture, petalling in Weldox 460 E steel projectiles, and shear cracking in 2024-T351 aluminum alloy projectiles. It should be noted that Weldox 460 E steel is much ductile than 2024-T351 aluminum alloy. Anderson et al. [16] conducted several Taylor impact tests and examined the ability of numerical simulations to reproduce ductile damage as a function of impact velocity. Test results showed that ductile fracturing occurs around the circumference at the projectile impact end. Numerical simulations indicated that it is insufficient to describe the ductile damage observed in the Taylor experiments by using the equivalent plastic strain as the sole indicator of damage. Chen et al. [17] observed sunflower-like petalling as well as mushrooming by firing soft blunt projectiles onto hard targets. Furthermore,

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Nomenclature

D_i	initial diameter of a projectile
D_f	impact end diameter of a projectile
L_i	L_f projectile length; initial and final, respectively
L_{unc}	length of the rear part of a deformed projectile over which the diameter keeps the initial value
m_i, m_f	projectile mass, initial and final, respectively
V_0	initial striking velocity

they found that soft projectiles could perforate the hard targets in some tests at high impact velocities. Xiao et al. [18] experimentally and numerically investigated the deformation and fracture behavior of 7A04-T6 aluminum alloy projectiles by Taylor impact test. Three deformation and fracture modes, mushrooming, shear cracking and fragmentation, were identified with increasing striking velocities.

Thus, the literature review indicates that possible projectile deformation and fracture modes are mushrooming, tensile splitting, void growth, and petalling for projectiles of high ductility, and mushrooming, shear cracking and fragmentation for projectiles of low ductility. It should be noted that the confined fracture reported in Ref. [15] is of the same mechanisms as the void growth found in [14], and that the mechanisms behind the petalling found in Refs. [15,17] is tensile splitting. In contrast, the petalling observed by Chapman et al. [14] is probably different, as stated earlier.

It is evident from the literature review, however, that the investigation on projectile deformation and fracture behavior in the Taylor impact test is limited and patchy. Especially, reports regarding the effect of projectile hardness are few. Furthermore, it is difficult to make comparisons between the results from different investigations because various projectile materials, such as aluminum alloys [14–16,18], steels [11,15,17] and tungsten alloys [12], are involved. At present, the effect of projectile hardness on the projectile deformation and fracture modes is therefore not clear enough. Further detailed study, especially experimental investigation, is required.

In the current investigation, a series of Taylor impact tests were conducted to investigate the effect of projectile hardness on the deformation and fracture behavior of flat-nosed projectiles. 38CrSi steel projectiles with two hardness values were obtained by two different heat treatment methodologies. A two-stage compressed gun test facility was used to accelerate projectiles to impact velocities from 200 to 600 m/s. According to the test results, four distinct deformation and fracture modes were identified, i.e., mushrooming, shear cracking, petalling and fragmentation. Relatively low velocity impacts result in the first two modes in both groups of projectiles, while high velocity impacts result in petalling and fragmentation in the soft and hard projectiles, respectively.

2. Experimental program

2.1. Experimental setup

A two-stage compressed gas gun test facility installed at Hypervelocity Impact Research Center in Harbin Institute of Technology was used to conduct the impact tests. The gun mainly consists of a pressurized chamber, a 57 mm caliber diameter nitrogen pump tube, a 12.7 mm caliber diameter and 3 m long launch tube, an impact chamber, and a measurement tube. The measurement tube lets the projectile has a 0.5 m free flight and the tube offers a space to have the initial velocity measure device installed. Beyond this, the tube connects the launch tube, the impact chamber and also the fixture tube, which provide a support to the target plates. The striking velocity is controlled by the pressured gas (pressure and kinds of gas: hydrogen/nitrogen) and through the selection of the diaphragm material (steel or aluminum) as well as its thickness. One couple of lasers placed at the muzzle of the launch tube is used to trigger the timing device and to get the exit velocities. The impact process was recorded with an Ultima APX-RS high-speed camera. One set of the lasers for exit velocity measurement was used to trigger the camera. Fig. 1 shows the sketch of the compressed gas gun.

The hard steel target was fixed to the end cirque of the fixture tube by three bolts, as shown in Fig. 2.

2.2. Projectiles and target plates

In this study, the impact tests were performed on cylinders manufactured from 38CrSi steel rods. The received rod diameter is 15 mm. All projectiles were machined from the original rods to cylinders of a nominal diameter $D_i = 12.62$ mm and a nominal length $L_i = 50.48$ mm ($L_i/D_i = 4$). To give birth to projectiles of two hardness values, half of the projectiles were heat treated for hard rods and the other half were kept original for soft projectiles.

Table 1 shows the hardness test results for projectiles selected at random. As shown, the hard projectiles are much harder than the soft projectiles and the hardness of the hard projectiles is 2.75 times of that of the soft projectiles. Preliminary uniaxial tension test on

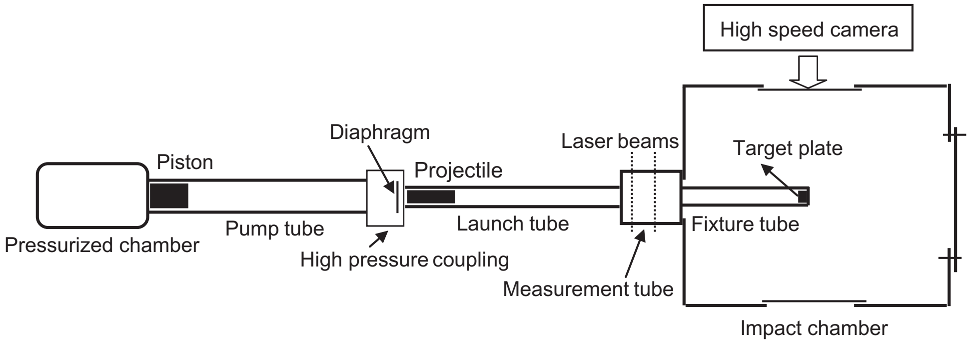

Fig. 1. Sketch of the two-state compressed gas gun.