Explosively driven ball bearings: flight behaviour and ball bearing damage

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Abstract. This paper describes findings from a series of experiments and computational simulations examining the flight characteristics of ball bearings and their ensuing damage. The results show the influence of ball bearing diameter and mass, charge mass and aspect ratio on the maximum and average ball bearing velocities, the influence of blast wave reflections on ball bearing momentum, and the role of internal pressure reflections on spalling/cracking failure of the ball bearings during flight.

Introduction

Ball bearings, and similar solid objects, are often embedded in explosives during the construction of improvised explosive devices (IEDs). These IEDs cause thousands of deaths and injuries every year [1], due to the blast wave and the solid projectiles ejected during the explosive event. This paper describes a series of experiments examining the flight characteristics of ball bearings and their ensuing damage. Understanding the behaviour of blast-driven ball bearings embedded in explosive charges will aid in the development of blast protection from IEDs. One of the great difficulties in IED research is the wide variety of possible configurations. Hence, a fundamental understanding of the momentum transfer mechanisms to embedded solid particles, and the damage to those solid objects caused during the event, is needed. This can be done by detonating an "idealised" explosive (PE4 plastic explosive shaped into a cylinder) with ideal solid objects (in this cases, ball bearings) and measuring the ball bearing velocity. This will allow model validation at the fundamental level so that more complex models representing real IEDs can be developed with confidence.

Experimental description

A simplified IED was developed. As shown in Fig. 1, a 5 mm diameter SS420-c spherical ball bearing was half embedded in a rear-detonated cylindrical charge. Tests showed that the ball bearings had a hardness of 628-648 (HV10), suggesting a range of 2098-2173 MPa for UTS [4], and a yield strength of 1685 ± 100 MPa [5] for martensitic metals. The ball bearing does not appear to be case hardened as the etched bearing cross-sections showed a consistent microstructure. PE4 explosive charge masses ranging from 2.2 g to 27 g were used to conduct a series of small-scale blast tests. The ball bearings were allowed to impact an aluminium witness plate. The impact crater depth was used to infer the impact velocities of the ball bearing by comparing against results obtained from a separate series of impact tests using a light gas gun. The witness plate was supported by a Hopkinson Pressure Bar (HPB) of equal diameter. The HPB was used to infer the in-flight velocity of the ball bearing. The detailed experimental arrangement is presented in refs [2,3]. Computations simulations performed using Ansys Autodyn were validated using the experimental measurements and then used to elucidate further insights into the ball bearing flight characteristics.

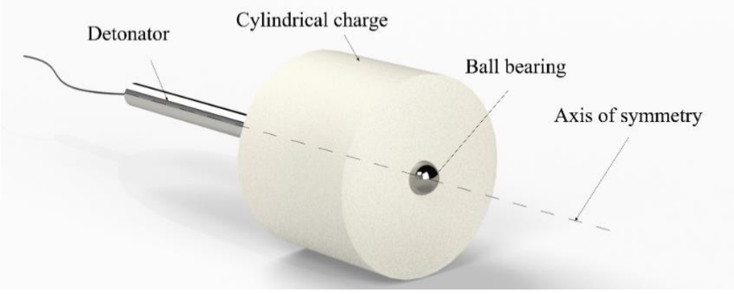

Figure 1: Schematic showing a rear-detonated PE-4 explosive cylindrical charge with a ball bearing half-embedded in the front flat face

Results

The experimentally informed computational simulations showed that the ball bearing flight could be divided into five phases based on the driving mechanisms within each zone:

- Detonation initiation to completion: ball bearing acquires momentum
- Shock front overtakes ball bearing, decreasing ball bearing acceleration
- Ball bearing velocity plateaus, insignificant pressure difference across bearing ball

- Pressure wave reflections interact with ball bearing, causing drop in velocity
- Recirculated gas products merge, ball bearing velocity stabilizes until impact with witness plate

The initial momentum transfer to the ball bearings depended on the charge mass and aspect ratio of the explosive [2]. Longer charges (higher L/D ratios) increased the initial (maximum) velocity of the ball bearing up to a critical aspect ratio after which the velocity increase occurred at a slower rate. Later work showed that the ball bearing characteristics (mass and diameter) were also significant with respect to the charge mass [3]. Momentum transfer, hence maximum ball bearing velocity, occurred during phase 3, and was mainly influenced by the charge mass to ball bearing mass ratio and the aspect ratio of the charge. Larger ball bearings require extra momentum to accelerate them to higher velocities due to their increased mass, but their higher surface area also means that a greater portion of the explosive charge was involved in momentum transfer. The drop in velocity experimentally observed part-way through the bearing flight (phase 4) was due to interaction with the reflected pressure. Modelling showed this was influenced by bearing diameter charge diameter - higher momentum required greater reflected pressures to decelerate the bearing, but the reflected pressure acted over a larger surface area. Additionally, less of the charge mass directly contributed to the reflected pressure front in low diameter charges; this was due to the increased bearing surface area meaning that less of the blast pressure moved past the ball bearing in the early stages of blast wave formation.

Post-test damage analysis of the recovered ball bearings showed consistent failure features: a change in shape from spherical to ellipsoidal (Fig. 2a) with the maximum circumference around the equator. The major damage feature was internal cracking, with pitting, surface cracks, fragmentation and streak marks also observed. Modelled showed tensile spalling was responsible for the presence of internal cracks (Fig. 2). The initial compressive hydrostatic pressure propagated across the ball bearing from the embedded side (face B) (Fig. 2c). The compressive stress then reflected from the free surface of the bearing (face A) as a tensile wave and was focused due to bearing curvature. The charge geometry influenced the magnitude and shape of the tensile spalling wave, affecting the location and degree of internal cracking within the ball bearings.

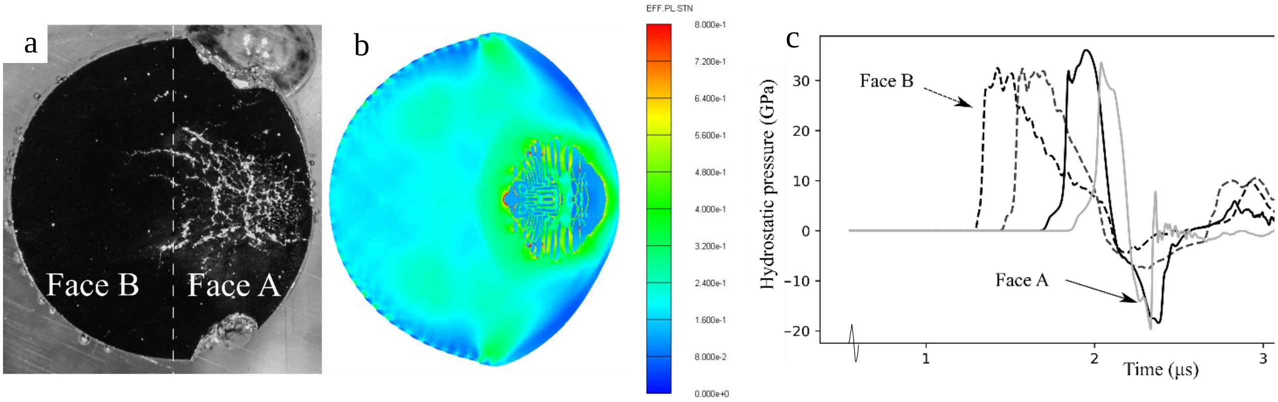

Figure 2: Comparison of (a) sectioned ball bearing (5.13g PE4), (b) the simulated effective plastic strain 2.5 μs after detonation, (c) Simulated pressure-time history inside the ball bearing for Face B (embedded) and face A (opposite to blast)

Conclusions

The findings show the value of using experiments and computational simulations together to gain greater insights into complex problems, such as IED analysis. The findings show the critical importance of charge mass, L/D ratio, ball bearing mass and diameter on early stage momentum transfer and subsequent flight response to reflected pressure waves. The work also shows that ball bearings are damaged due to the detonation and failure due to tensile spalling. This changes the shape of the bearing prior to impact and could also affect the flight if the cracking is severe enough to break the ball bearing apart.

References

[1] I. Overton, J. Dathan, C. Winter, J. Whittaker et al. *Improvised explosive device monitor 2017,* Action On Armed Violence. AOAV Tech Rep (2017).

[2] R. Qi, G.S. Langdon, T.J. Cloete, S. Chung Kim Yuen, *Behaviour of a blast-driven ball bearing embedded in rear detonated cylindrical explosive*, Int J Impact Eng, 146:103698 (2020).

[3] G.S. Langdon, R. Qi, T.J. Cloete, S. Chung Kim Yuen. *Influence of ball bearing size on the flight and damage characteristics of blast-driven ball bearings*. Appl Sci, 12(3):1133 (2022).

[4] DIN 50150 Testing of Steel and Cast Steel; Conversion Table for Vickers Hardness, Brinell Hardness, Rockwell Hardness and Tensile Strength, Beuth Verlag GmbH: Germany (1976).

[5] E.J. Pavlina, C.J. Van Tyne. *Correlation of yield strength and tensile strength with hardness for steels*. J. Mater. Eng. Perform. 17:888–893 (2008).