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Modelling the formation of explosively formed projectiles (EFP)

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ABSTRACT

The number of victims of attacks from improvised explosive devices (IED), especially from roadside bombs where explosively formed projectiles (EFP) are frequently used, has steeply increased until 2011. Understanding these threats, how they are built and predicting how they interact with targets is of utmost importance. For this purpose it is first necessary to understand how EFPs are formed and what parameters influence their behaviour and performance. The work in this paper proposes and describes a numerical simulation methodology that allows to reproduce the conditions of formation and ballistic capabilities of explosively formed projectiles. Different EFP configurations, materials and detonation conditions are evaluated and assessed against the performance (*e.g.* stable flight velocity) of the resulting projectile. The model proposed is based on a generic EFP with an aspect ratio of approximately 1 and a case/base thickness of 5 mm. The dynamic interactions between the various components of the EFP are established through specific contact algorithms that allow to interpolate the resulting pressure from detonation to the remaining components, resulting in their acceleration and consequent deformation. The model is validated against experimental observations and afterwards used to assess the influence of the liner materials and thickness, high-explosive, number and off-centre distance of detonators. The performance of the EFPs is quantified from their configuration and a set of non-dimensional geometrical parameters. It is shown that the thickness (and thickness variability) of the liner is one of the most important factors, along with the off-centre distance of the detonator(s). Within the materials and range of parameters tested, the most performant and aggressive EFP has a liner with thickness between 4 and 7% of its diameter, a copper liner and dynamite high-explosive (HE).

1. Introduction and state-of-the-art

Shock waves from the detonation of an high-explosive (HE) can be used to deform and warp a liner of ductile metal, forming explosively formed projectiles (EFP), also known as self-forging fragments (SFF). These compact projectiles can reach velocities in excess of 1000 m/s, with the consequent kinetic energy.

The first publications with reference to devices similar to present-day EFPs appeared in 1935 [1] and 1936 [2]. However, it was not until the 1970s that related studies significantly increased. Johnson [3] firstly demonstrated the existence of three-dimensional numerical modelling capabilities of the explosive-metal interaction using complex surfaces. To this end, this author used the example of an explosive that accelerates a metal projectile after detonation. This study investigated: (i) the effect of shell (liner) thickness, from $0.9t_0$ at the edge of the liner up to $1.1t_0$ in its centre (t_0 being the thickness of a projectile with an equivalent mass), (ii) the effect of an off-centre detonation and (iii) the effect of an uneven distribution of the density of the high explosive. It was shown that these parameters significantly influence the stable flight velocity of the projectile. More recently, Johnson [4] explored issues related to modelling three-dimensional EFP, explaining the effects of the contact interface, discretisation and finite element approach. Similar computational topics were extensively researched by Zukas et al. [5], Taylor [6], Nyström et al. [7] and Molinari [8], focusing on aspects such as the effect of meshing, blast load intensity, constitutive modelling and the use of alternative methods (*e.g.* smooth particle hydrodynamics, SPH).

Geometrical parameters are known to play an important role on the formation of an EFP. Miller [9] and Brown et al. [10] provided a set of EFP design criteria based on projectile velocity or mass concentration. Weickert et al. [11] and Chuan et al. [12] discuss different design approaches, focusing on target penetration. One of the most significant and influential parameters is the aspect ratio (length-to-diameter ratio) of the explosive before detonation, which led Bender and Carleone [13] to conclude that the kinetic energy of the projectile increases with this ratio up to a maximum of 1.5. Another important observation was the effect of adding mass to the casing, increasing the duration of the shock wave propagation and

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consequently the total energy transferred to the projectile. Weimann [14] and Weickert and Gallagher [15] demonstrated that adding a reinforcement ring to the case and liner has a significant effect on the shape, configuration and velocity of the resulting EFP, eventually even providing fins that aerodynamically stabilise the projectile during its flight. Bender and Carleone [16] submitted a patent in 1994 explaining the use of a thin radial spacer between the projectile and the high-explosive, leading to periodic thickness variations and, consequently, the formation of fins.

Pappu and Murr [17] analysed, both experimentally and numerically, the characteristics of residual microstructures of several EFPs, testing three different liner materials (tantalum, iron and copper) using two constitutive models for each material (Johnson-Cook [18,19] and Zerilli-Armstrong [20]). They concluded that, although the selected materials have been widely used in EFP [21–24], they lead to completely distinct behaviour, influencing the melting temperature and the mechanisms by which the crystal structure deforms. The Zerilli–Armstrong model [20] led to better results for tantalum (Ta) projectiles, unlike iron (Fe) that exhibited better results with the Johnson–Cook model. Results were similar, however, for the copper (Cu) projectiles.

More recently, Wu et al. [25] studied the formation, flight and penetration performance of EFPs using a single geometric configuration with an Arbitrary Lagrangian-Eulerian (ALE) approach. These authors considered air drag during flight through an attenuation rate equation for a fixed flight distance (of 48 m). The projectile velocity was analysed both with the similarity theory and the numerical simulation results, which were validated by experimental residual velocity measurements after impact on a 25 mm ballistic steel target. It was concluded that it is still possible to optimise the geometry of the EFP by combining the shape of the explosive and liner. As simulating the flight of the EFP is complex and impractical, only 0.5 m of flight were analysed, nonetheless leading to reasonably accurate results. The attenuation method can be considered accurate, with a loss of speed of approximately 6.4 m/s per meter of flight, consistent with the experimental results. The use of the similarity theory can be useful to solve technical problems associated to the determination of the entire flight of the EFP: the error obtained on the residual velocity for a 0.5 m flight is lower than 10%. Finally, by comparing the velocity and penetration on the target results, Wu et al. [25] concluded that simulations can reasonably predict the final shape, mass, velocity, flight stability and penetration performance of an EFP.

Li et al. [26] examined the effects of the position, timing and number of detonation points on the formation of the EFP, concluding that the stable flight velocity of the projectile increases with the number of detonation points, observing that for a 60 mm diameter EFP the signal delay between detonators should not be above 200 μs. Experimental results confirm that for certain flight distances the penetration capacity doubles and the perforation diameter reduces by as much as 40%.

According to statistics published by the Center for Strategic & International Studies (CSIS) [27] and data from the US Department of Defense published by The Washington Post in 2011 [28] and 2014 [29], the number of casualties due to improvised explosive devices (IED) in Iraq strongly increased from 2009 to 2010, with increases as high as 60% on some periods. Although these numbers have been dropping steadily since 2010 (IED casualties have dropped by 48% in 2012 alone), IEDs and EFP devices in particular are still, and will remain, a significant threat in years to come. It is thus highly relevant to develop efficient and reliable means of assessing and predicting the behaviour of such devices, in the end leading to the development of technologies, methods and systems that can better protect against them. The main aim of the present paper is then to contribute to this, with a methodology, a finite element modelling approach and formulation, as well as the corresponding formulations, reproducing the conditions of formation and ballistic capabilities of EFPs.

2. Numerical model

2.1. Geometry and boundary conditions

When developing the numerical models, attention was given to the accurate reproduction of the boundary conditions and geometrical configurations. The work of Wu et al. [25] was used as reference and for validation purposes. The proposed geometry is that of a generic EFP, as shown in Fig. 1, with a length-to-diameter ratio $L/D = 1.07$, liner of diameter $D = 56$ mm, thickness $e = 2$ mm, curvature with radius $R = 120$ mm and sweeping angle $\alpha = 29°$. The casing and the base have thickness $e' = 5$ mm. The remaining dimensions will change according to the specific model being tested. The complexity of the dynamic interactions between the various components of the EFP (*e.g.* explosive-metal interaction) leads to a detailed and costly modelling process. Interactions between the products of detonation and the remaining components of the EFP are defined using a specific contact algorithm that can model surface sliding and is based on a master-slave segments approach. With this algorithm pressure values are interpolated and passed to the remaining components of the EFP, leading to their acceleration and consequent deformation.

The symmetry boundary conditions used in the numerical models are schematically shown in Fig. 2. This allows models to run with a significantly lower computational cost. Fully three-dimensional models were used however, where no symmetry is present.

The detonation point – its position and detonation time (*e.g.* see Fig. 2) – defines the instant and geometrical coordinates of ignition, dictating the behaviour of the shock wave and the subsequent deformation and flight of the projectile.

2.2. Material modelling

Different materials were used to allow for the study of different EFP configurations. These include OFHC copper, ARMCO iron and tantalum as liners; Octal, composition B (CompB) and dynamite as high-explosives; and steel 1006 and aluminium alloy 6061-T6 for the casing and base of the EFP, respectively. The properties of the materials used were validated using numerical and experimental results previously published by other authors, who have studied their behaviour in similar situations and strain rate regimes [17,18,25].

Materials are subjected to high pressure, temperature and high deformations and strain-rates during the formation of the EFP.

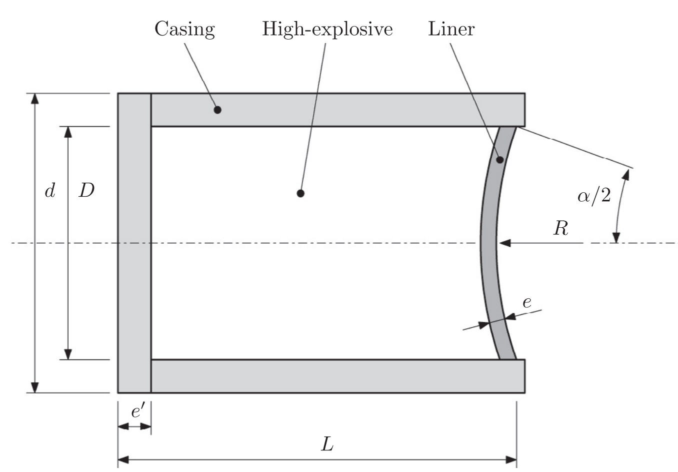

Fig. 1. Schematic representation of the generic EFP geometry.