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Ballistic resistance of 2024 aluminium plates against hemispherical, sphere and blunt nose projectiles

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ABSTRACT

Numerical investigation has been carried out on 2024 aluminium plate targets against 12.7 mm diameter hardened steel projectiles. The ballistic resistance of 1.27 mm thick target was studied against a spherical ball as well as the hemispherical and blunt nosed cylindrical projectiles. The simulations were performed on ABAQUS/Explicit finite element code by modelling the target as deformable and the projectiles as rigid three dimensional surface. The Johnson-Cook (JC) elasto-viscoplastic material model was employed to predict the flow and fracture behaviour of the target. The objective of the study was to investigate the efficiency of the JC model to numerically reproduce the maximum target deflection and peak impact force caused by three distinct shaped projectiles during target perforation. Three different sets of JC parameters calibrated by different authors [20,21] for 2024 aluminium alloy were considered to simulate the performance of the target against each projectile and the results thus obtained were compared and validated through available experiments [24]. The failure mode, deflection and impact force obtained have been noticed to have significant influence of the material models. The ballistic limit of 1.27 mm thick target was numerically computed against each of the three projectiles and validated through the Recht-Ipson model. The effective span and target thickness were also varied to investigate the influence on the maximum deflection and peak impact force.

1. Introduction

Advance commercial computer codes and sophisticated material models are available to describe the behaviour of metals under high speed impact loading. However, the material parameters are often not available in the open literature to simulate high strain rate/elevated temperature effects which are prominent in ballistic impact problems [1–10]. Also, the insight of the numerical modelling and the influence of model parameters is not explored and most of the ballistic studies are based on experimentation [11,13,14].

Alfaro-Bou and Thomson [11] conducted ballistic experiments on 2024 aluminium targets of 0.5–6.5 mm thickness to obtain ballistic limit. The projectile (plastic disc) velocities ranging from 1 to 8 km/s and plastic disc diameter 6.4 and 9.5 mm with 10 and 30 mg respectively. The experimental ballistic limit correlates well with the theory based visco-plastic model proposed by Thomson and Kruszewski [12]. Goldsmith and Finnegam [13] carried out experiments on 2024 aluminium targets against normal and oblique impact of cylindro-conical and cylindrical projectiles velocity up to 1 km. They examined post impact target damage, dishing, petals, plugs and bands separated from the crater to understand ballistic behaviour. Gogolowski and Morgan [14] carried out ballistic experiments on 2024 aluminium targets of 1.27, 2.54, and 3.81 mm thickness against fragment simulant projectile, circular cylinder projectile with fineness ratio of 1.0 and circular cylinder projectile with fineness ratio of 0.2. The failure mode of target was observed from petaling to plugging as plate thickness increases from 2.54 and 3.81 mm. Kelley and Johnson [15] studied ballistic response of 1.6, 3.18 and 6.35 mm thick 2024 aluminium, 6.35 mm thick titanium, polycarbonate and composite targets against 12.52 mm diameter steel spherical projectile. The ballistic limit was obtained for each set of targets and failure modes were evaluated. It was concluded that the excellent results was observed on 2024 aluminium but more data is needed for titanium, composites, and polycarbonate materials. Buyuket al. [16] conducted ballistic experiments on 2024 aluminium targets of 1.6, 3.18 and 6.35 mm thickness against spherical projectiles. The ballistic limit found experimentally for 1.58, 3.17 and 6.35 mm target was 122, 213 and 411 m/s, respectively, and it was reproduced through finite-element simulations with good agreement. The performance of numerical simulations is discussed in terms of material characterization, material model para-

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meters and mesh sensitivities. It was observed that mesh refinement does not necessarily provide better results for ballistic limit simulations without considering and calibrating these interrelated factors. It was also observed that transition of failure mode makes it impossible to change deformation and failure by using a single set of parameters. Hub et al. [17] carried out ballistic experiments and 2D finite element simulations on 1.2 mm thick 2024-T3 aluminium against 9 mm calibre pistol projectile. A good correlation between the experimental and simulation results was observed in terms of comparison of residual velocities. Seidt et al. [18] carried out experiments on 3.18 and 12.7 mm thick 2024-T3 and T351 aluminium target, respectively against titanium and tool steel projectiles. The simulations were carried out with two sets of material parameters to study the effect of isotropy and anisotropy on ballistic performance of 2024 aluminium target. It was observed that the material parameters considering anisotropy in the material behaviour reproduced results in better agreement with experiments than the material parameters based on isotropic behaviour. Jones and Paik [19,20] developed few empirical equations to estimate the perforation energy of structural aluminium and steel plates against low and intermediate impact velocity. Several empirical equations developed recently, have been examined for their accuracy in estimating the perforation energy of metallic plates. It was concluded that empirical equations are valuable for preliminary design purpose and sometimes adequate for the final design. Zhan et al. [21] carried out a series of experiments to explore the impact characteristics of stiffened plates against ogival nosed projectile with initial velocities in the range 546–618 m/s. The ballistic resistance of stiffened targets at the nine different locations are measured, and the data is in good agreement with the proposed mathematical model. Paik and Won [22] developed a new empirical formula for estimating the impact energy absorbed up to perforation of the target plate. The developed empirical formula was capable to cover a wider range of the impact velocities up to 800 m/s, while the existing formulae were valid up to 120 m/s incidence velocities. The ballistic experiments performed by Jones and Kim [23] on thin plates (4, 6 and 8 mm) were also reproduced numerically and the experimental as well as numerical findings were compared with that of the developed empirical formulae.

The influence of constitutive models and individual model parameters on the ballistic response is not much studied in the literature. Aluminium alloy 2024-T3 has applications in primary structural elements of aircraft such as fuselage, wings and shear webs where the stiffness and strength are essential requirement. Aerospace structures are subjected to different types of loadings starting from static to shock, vibration and impact, during its service life, and therefore requires investigation of its structural material under impact loading.

In the present study, the numerical investigations were carried to explore the maximum impact force and corresponding deformation characteristics of 2024 aluminium alloy targets against spherical ball and hemispherical and blunt cylindrical projectiles. The impact velocity of projectile was varied as 23–82 m/s and the geometry of the target and projectile was considered identical to that employed in [24]. The Johnson-Cook (JC) elasto-viscoplastic material models calibrated by Lesuer [25] and Kay [26] were employed to perform numerical simulations on ABAQUS/Explicit finite element code. Three different sets of JC parameters were employed to investigate the target performance against distinct shaped projectiles. The results obtained with respect to force, central deflection and fracture of target were compared and discussed. Target thickness (0.75, 1.27, 1.80, 2.40 and 3.18 mm) and span (20, 40, 80, 100, 119, 200 and 360 mm) were also varied to study the ballistic performance against hemispherical projectiles.

2. Finite element modelling

The finite element model of the target and the projectile was made using three dimensional modelling approach in ABAQUS. The finite element model of the target and three different projectiles shown in Fig. 1(a)–(c) have been made in accordance with the geometries employed in Levy and Goldsmith [24]. The shank diameter, shank length, nose length and total length of the hemispherical projectile were 12.7, 34, 6.35 and 40.35 mm, Fig. 1(a). The diameter of the sphere, Fig. 1(b), was 12.7 mm and mass, 8.4 g. Similarly, the shank diameter of the blunt nose projectile, Fig. 1(c), was 12.7 mm and total length of projectile, 40.35 mm. The mass of the hemispherical and blunt nose projectiles are in the range of 36.2–39.5 g [24]. The circular target of diameter 119.4 mm was modelled as deformable body and assigned fixed boundary conditions at the periphery. The projectiles in the present study were modelled as analytically rigid due to their high rigidity in comparison to the thin aluminium targets. Levy and Goldsmith [24] also confirmed that no permanent deformation of projectile was observed in any of their experiments. The projectile was assigned initial velocities equivalent to those obtained by Levy and Goldsmith [24]. The contact between the projectile and target was modelled by employing the Kinematic contact algorithm. The projectile was considered as master and the contact surface of target as slave surface. In the normal direction hard contact was defined and in the tangential direction the effect of friction has been assumed to be 0.035 for hemispherical and blunt projectiles while friction was neglected for sphere ball.

The mesh sensitivity in the target was studied by varying the element size as 0.8, 0.6, 0.4 and 0.2 mm^3 in the impact zone corresponding to 2, 3, 6 and 12 elements at the target thickness. The hemispherical projectile was impacted normally at an incidence velocity 82 m/s on 1.27 mm thick target and the residual velocity was found to be 61.77, 61.46, 61.38 and 61.08 m/s respectively, see Fig. 2(a). The mesh sensitivity of target with respect to residual velocity was found insignificant, however, the mode of failure significantly affected by varying mesh size, see Fig. 2(b)–(e). The failure mode of the target compared with the experiment, see Fig. 2(f), was found in good agreement when the element size was 0.2 mm. The size of element was therefore considered to be 0.2 mm^3 and the aspect ratio unity in all the simulations. Away from the impact region, however, the size of element was slightly increased keeping the aspect ratio unity. Three planar zones were identified with diameter 15, 28 and 40 mm and the element size was kept 0.2, 0.6 and 0.8 mm^3 respectively. The compatibility between the varying sizes of elements was maintained using the tetrahedral elements in the transition zones.

3. Constitutive modelling

The computational model based on the viscoplasticity and continuum damage mechanics employed in the present study was proposed by Johnson and Cook [1,2]. It includes linear thermo-elasticity, the von Mises yield criterion, the associated flow rule, isotropic strain hardening, strain rate hardening, softening due to adiabatic heating and a failure criterion. The static yield stress of the model is defined as;

$$\sigma^0 = [A + B(\bar{\varepsilon}^{pl})^n][1 - \hat{T}^m] \tag{1}$$

Where $\bar{\varepsilon}^{pl}$ is equivalent plastic strain and *A, B, n* and *m* are material parameters measured at or below the transition temperature, T_0. The non-dimensional temperature $\hat{T}$ is defined as;

$$\hat{T} = \begin{cases} 0 & \text{for} \quad T < T_0 \\ (T - T_0)/(T_{melt} - T_0) & \text{for} \quad T_0 \le T \le T_{melt} \\ 1 & \text{for} \quad T > T_{melt} \end{cases} \tag{2}$$

Where T is the current temperature, T_{melt} is the melting point temperature and T_0 is the transition temperature defined as the one at or below which there is no temperature dependence on the expression of the yield stress. When $T > T_{melt}$, the material melts down and behaves like fluid and hence does not offer shear resistance i.e., $\sigma^0 = 0$.

The Johnson-Cook strain rate dependence assumes;