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Energy absorption in thin metallic targets subjected to oblique projectile impact: A numerical study

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ABSTRACT

The present study investigates the ballistic performance and energy absorption in plastic deformation due to work done in radial, circumferential, axial and tangential directions in 1 mm thick aluminum 1100-H12 targets. The targets were impacted by single nosed; ogival, blunt and double nosed; ogival-blunt and blunt-blunt, EN-24 Steel projectiles at 0°, 15°, 30° and 45° oblique incidence angles. Three-dimensional models of both projectiles and the targets were created and numerical analyses were performed in Abaqus Explicit solver. Ballistic performance, mode of failure and energy absorption in the target were compared within the configurations. Targets impacted with double nosed projectiles exhibited higher ballistic limit, followed by single nosed blunt and then by ogive nosed projectile. Single nosed ogive projectiles, showed increase in ballistic limit with the obliquity, whereas blunt, ogival-blunt and blunt-blunt projectiles displayed opposite behavior. The energy absorption in targets subjected to ogival-blunt projectile was found to be highest, followed by targets subjected to blunt-blunt projectile, then single nosed blunt and ogive projectile in the last. Further, total energy absorption in the targets subjected to ogive nosed projectile was increased with the obliquity, whereas, in case of blunt and double nosed projectiles, the energy dissipation was reduced.

1. Introduction

The ballistic performance and the failure mode of thin ductile targets significantly depend upon various parameters, viz. incidence velocity, material of the target and projectile, shape of the projectile and angle of impact or incidence angle. The shape of the projectile greatly influences the failure pattern of the target. For thin ductile targets, there are two common failure modes described by Backman and Goldsmith [1]. Petaling is associated with the ogive or conical nosed projectile whereas plugging of the target is seen in case of blunt nosed projectile. During ogive nosed projectile impact, petals are formed by high radial and circumferential tensile stresses. As the projectile tip penetrates through, the contact material starts yielding and a star-shaped crack is formed which eventually results in the formation of petals due to further progress in perforation process. Plugging failure in the target is observed as a result of shearing, in which formation of narrow shear bands at the periphery of blunt nosed projectile leads to the plug formation. These local failures in the thin target are accompanied with the large global plastic deformation in the target in the form of permanent flexure knows as dishing. In the past studies, various researchers portrayed the behavior of thin ductile targets impacted by projectiles at oblique incidence angles [2–11] but a very few studies were undertaken to evaluate energy absorption due to the plastic work done during impact.

Awerbuch et al. [2] performed analytical and experimental study involving the mechanics of impact behavior of metallic plates when subjected to oblique impact. The experiments were carried out using 0.22 in. caliber lead bullets on 2.0–6.0 mm thick aluminum and aluminum alloy target plates. A previously developed analytical model was modified to predict the post perforation velocity and found in good collaboration in experimental results. However, for large impact angle, the analytical approach showed significant deviation and did not fully described the failure of target. Goldsmith and Finnegan [3] presented an extensive experimental database involving about 200 tests, in which aluminum, mild and medium carbon steel targets of thickness ranging from 1.25 to 25.4 mm, were impacted by hard steel projectiles with 60° conical or blunt tips and blunt soft aluminum strikers, both of 12.7 mm diameter. The velocity drop in the residual velocity was measured as angle of inclination was increased. The initiation of failure modes of targets was observed and it was found that the effect of obliquity

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completely changed the petal patterns in both thin and thick targets. Gupta and Madhu [4] investigated the ballistic performance of 10–25 mm thick mild steel plates impacted by a spinning armor piercing projectile at various angles of obliquity. The incidence angle was increased from normal impact (0°) until the ricochet was observed. The velocity drop curves for various oblique angles were presented and analytical relations were then developed between the drop, thickness of plate and angle of obliquity, which were found in good agreement with the experimental results. Gupta and Madhu [5] presented an experimental study in which single and layered targets of mild steel, RHA steel and aluminum were impacted by armor piercing projectile at various oblique angles. An analytical relation for determining thickness of plate for which the incident velocity is the ballistic limit was obtained. It was found that the angle of exit of projectile from target after impact was different than the incidence angle. The velocity drop for all the targets was found to be increased with the incidence angles. Madhu et al. [6] extended the previous study [5] and evaluated the performance of single and layered targets against ogive nosed hard steel projectile at different incidence angles until ricochet occurred and shown similar behavior in velocity drop across all the targets as in the previous study. Khan et al. [7] developed an analytical model for calculating residual velocity of the projectile in oblique impact. Experiments were performed to corroborate the analytical model using aluminum plates of different thicknesses and impacted by hardened cylindrical steel projectiles at three angles of incidence. The analytical model was based on the computation of energy absorbed in targets which was then observed mainly due to radial dishing along with the shearing of plug at the time of impact. The computed values shown good corroboration with observed experimental results. Gupta et al. [8] presented a numerical and experimental study on performance of layered aluminum plates subjected to blunt, ogive and hemispherical nosed steel projectiles. In case of two layered targets it was found that the residual velocities of the projectiles were comparable to that of the single plates of equivalent thicknesses. However, when the number of layers was increased, the single plate of equivalent thickness offered more resistance against perforation. Zhou and Stronge [9] presented numerical and experimental study involving a comparison of the ballistic resistance of monolithic and double layered sandwiched stainless-steel targets. All the targets were impacted by cylindrical steel projectile with either blunt or hemispherical nosed shape at various angle of obliquity (0°, 30° or 45°). It was observed that at all the angles, blunt nosed projectile has a smaller ballistic limit than a hemispherical projectile. The behavior of targets was varied with the angle of obliquity and directly influenced with the mode of failure at the time of impact. Iqbal et al. [10] performed three dimensional numerical simulations to study the response of aluminum and Weldox steel targets subject to oblique impact by ogive nosed and conical nosed projectile at 0°, 15°, 30°, 45° and 60° incidence angles. It was observed that as the incidence angle increases the deformation mode was changed from circular hole to elliptical hole in case of 12 mm thick steel targets, whereas in 1 mm thick aluminum targets the number of petals were decreased, however the size of the side petal increases and emerged from elliptical bulge. The ballistic performance in both the cases was found to be increased with obliquity. Iqbal et al. [11] investigated failure modes and ballistic resistance of aluminum targets subjected to double nosed projectiles. Three projectile shapes, viz. conico-blunt, blunt-blunt and blunt-conico were impacted normally on 0.82 mm and 1.82 mm thick targets of aluminum 1100-H14. Failure modes, deformation pattern and ballistic limit of both targets obtained in experimental and numerical studied were compared within targets impacted by single and double nosed projectile. The targets impacted with double nosed projectiles exhibited high ballistic limit than with single nosed projectile. Iqbal et al. [12] presented experimental and numerical investigation on the influence of target-projectile diameter ratio (D/d) on the ballistic performance, failure mechanism and energy absorption in aluminum targets impacted by blunt and ogive nosed projectiles. The ballistic limit obtained was found to be increased consistently with increase in D/d ratio against both projectiles. Energy absorption in the targets impacted by blunt nosed projectile was decreased with increase in D/d ratio, whereas, targets struck by ogive nosed projectile showed constant variation. Senthil et al. [13] studied ballistic response of 12 mm thick mild steel plates subjected to 7.62 API projectile at oblique incidence angles. The experimental and numerical results were compared in the aspects of failure mode, residual projectile velocity and critical ricochet of the projectile. It was observed that the resistance of target was found to be increased with incidence angle obliquity.

Past studies present ample amount of research work which include analytical, experimental and numerical approaches, that were applied to ascertain the ballistic performance of metallic targets and the mode of failure associated with the impact when subjected to different projectile nose shapes. A very few studies reported energy absorption during impact but did not clearly discuss the distribution of energy in different failure modes. The present study discusses the categorization of plastic work done in the target plate during the impact. The total plastic energy absorbed in 1 mm thick aluminum 1100-H12 target was bifurcated into four categories which were developed due to stresses and strain produced in radial, circumferential, axial and tangential directions, when subjected to projectiles at ballistic limit. The ballistic performance of the targets was compared when subjected to EN-24 Steel single nosed; ogival, blunt and double nosed; ogival-blunt and blunt-blunt projectiles of 19 mm diameter and 52.5 g mass, at 0°, 15°, 30° and 45° obliquity.

2. Numerical methodology

Three-dimensional models of 1 mm thick monolithic circular target of aluminum 1100-H12 and 19 mm diameter EN 24 Steel projectiles of single nosed; ogival and blunt, and double nosed; ogival-blunt and blunt-blunt shape and 52.5 g mass were developed using Abaqus/CAE module. Since all the targets were bolted at 230 mm pitch circle diameter, thus in numerical modelling, the targets were modelled as 230 mm diameter circular plate and kept fixed at boundary (Fig. 1). Projectiles were modelled as a rigid body due to negligible deformation experienced during impact, All the targets were modelled as a deformable body using eight node brick elements with reduced integration (C3D8R). Since there was negligible deformation observed in the experiments [8], thus in the present study, the projectiles were modelled as rigid body to optimize the computational time of the simulation. Senthil et al. [14] investigated the extent of deformation in a similar projectile impacted on aluminum targets and reported that due to relatively high strength of projectile material in comparison to the target, the projectile experienced negligible deformation during impact. The contact between the target and projectile was modelled using kinematic contact algorithm as given in ABAQUS 6.7-3 [15], in which outer surface area of the projectile was assigned as master surface and the contact region of the target as node based slave surface. The effect of friction was neglected between the contact surfaces of projectile and target, since friction remains insignificant due to very small contact duration under high speed impact problems [16,17]. A friction sensitivity [18] was also performed showing negligible influence of the friction on the performance of the targets. A mesh convergence study was carried to obtain optimum size of element without affecting the accuracy of the results (Iqbal et al. [19]). To reduce the computational time, partitions were made in the target as inner and outer contact zones. The mesh size in all the targets in inner contact area was taken to be $0.16 \times 0.16 \times 0.16\ mm^3$, keeping the aspect ratio as unity. Whereas, in outer contact the aspect ratio of the elements was varied accordingly as the diameter of plate was increased. To induce obliquity in incidence angle, the targets were rotated clockwise at 15°, 30° and 45° from the original position, instead of projectiles. Abaqus/Explicit module was used to perform all the dynamic explicit numerical simulations. All the targets were impacted at given incidence velocities until