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Energy absorption characteristics of thin aluminium plate against hemispherical nosed projectile impact

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ABSTRACT

The energy absorption characteristics of monolithic and layered aluminium plates made of aluminium 1100-H12 were investigated against hemispherical nosed projectile impact both experimentally and numerically. The span diameter of 1 mm thick monolithic plates were varied as 68, 100, 150, 200, 255, 350, 450, 550, 650 and 750 mm whereas the effect of target configuration were studied for monolithic (1 mm), layered in contact (0.5 + 0.5) and spaced target (0.5 + 0.5) of 150 mm free span diameter. The spacing between thin layers was varied as 4.5, 10, 20, 30, 40, 50 and 60 mm. Each target was impacted normally by 19 mm diameter hemispherical nosed projectile. Some of numerical results were validated with experimental results with varying target span diameter (68, 100, 150, 200 and 255 mm), layered in contact target and the target with 4.5 mm spacing. Numerical results were found to be quite close with experimental results. A pressure gun was employed to carry out the experiments while the numerical simulations were performed on ABAQUS/Explicit finite element code. Further numerical simulation results were used to calculate the energy dissipation in plastic deformation. The energy was further disintegrated in stretching in radial, circumferential, axial and tangential directions. Both the ballistic performance and energy absorption characteristics were significantly influenced by target span and configuration. The ballistic limit has been found to be significantly increased with an increase in the span diameter of the target. The monolithic target was found to be superior followed by layered in contact and spaced target.

1. Introduction

In current scenario thin metallic structures in the form of plates and shells are widely used in different engineering applications such as locomotive, automobile, naval, aerospace and different fabrication work. During their service life they experience different types of impact loading which may cause highly localised deformation. The crack propagation and fracture phenomenon are more prone towards these types of localised deformation that may be caused of a catastrophic failure. In depth understanding of impact phenomenon is required to design such structures so that damage can be mitigate. In this context, the response of thin plates against projectile impact has been addressed in the literature by varying parameters of projectile (mass, nose shape, angle of the incidence and hardness) and target (thickness, material, configuration and strength of the target). The influence of projectile nose shape on thin plates made of aluminium [1–3] and steel [4,5] has been studied both experimentally and through numerical simulation by varying the nose shape blunt, conical, ogive and hemispherical. The spherical nosed projectile was found to be least efficient penetrator [1–5]. For steel plates of thickness 1 mm offered maximum resistance against hemispherical projectile followed by ogive and blunt nosed projectile [4,5]. In general the ballistic resistance of monolithic target was highest followed by layered in contact and spaced target of equivalent thickness [6–11]. Ballistic limit decreased when the spacing between the targets was increased [10]. Against 7.62 mm standard bullets the ballistic resistance of layered plate improved as the number of layers decreased and the thickness of back plate increased [11]. However few studies reported opposite trend [12,13]. Against 0.22 in. caliber projectiles multi layer thin aluminium beams performed better than the monolithic beams of equivalent thickness [12]. Similarly two layered plate of 6 mm thickness made of Weldox 700 E steel showed better resistance as compared to 12 mm thick monolithic plate against blunt nosed projectile [13]. For ogive nosed projectile however, monolithic plate showed highest resistance followed by layered in-contact and spaced plates respectively. Similarly Corran et al. [14] also found that if the failure mode of individual layer changed from petalling and shearing to membrane stretching, the layered in contact target showed better ballistic resistance compared to monolithic plate

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of equivalent thickness. The ballistic performance of thin aluminium plate was also reported with varying span diameter against ogive and blunt nosed projectile and reported a significant increase in ballistic limit with increase in span diameter [15,16]. Moreover the effect was more prominent for blunt nosed projectile as compared to ogive nosed projectile.

Further the impact response of plates was explored by studying the energy absorption by the target when subjected to projectile impact [14,17,18]. The energy absorption in membrane stretching and elastic deformation decreased with increase in thickness of the target plate whereas opposite trend was reported for the energy absorption in bending and plugging [14]. The energy absorption in thin aluminium plate against ogive nosed projectile was explored by Gupta et al. [17]. For target thicknesses 0.74–2 mm, a major portion of the impact energy dissipated in radial stretching. With increase in target thickness, the energy absorption in crater formation decreased whereas in dishing it increased. According to Rusinek et al. [18] the total energy absorption by the target dissipated in plastic deformation, friction and inertial effects. However, at the ballistic limit the entire kinetic energy of the projectile absorbs by the target in the form of its plastic deformation. Subsequently, it decreased with further increase in projectile incidence velocity.

The studies wherein the span of the target has been studied are very limited. Moreover the influence of target configuration on ballistic performance is not much clear due to reporting of some contradictory results. The energy absorption by the target has been investigated based on some analytical expression by considering some assumptions which are not much accurate. Hence the influence of span and configuration on the ballistic performance and energy absorption characteristics of thin plates needs to be further investigated.

The present numerical study describes the effect of target span diameter and configuration on the ballistic resistance, failure mechanism, global deformation and energy absorption characteristics. 1 mm thick monolithic 1100-H12 aluminium targets of span diameters 68, 100, 150, 200, 255, 350, 450, 550, 650 and 750 mm were impacted by hemispherical nosed projectiles to obtain ballistic limit, v50. It is the average of the maximum velocity at which projectile could not perforate the target and minimum velocity at which projectile completely perforates the target. The configuration of 150 mm span diameter targets of 1 mm equivalent thickness was also varied as monolithic, double layered in-contact and double layered spaced. Spacing between the 0.5 mm thick layers was varied as 4.5, 10, 20, 30, 40, 50 and 60 mm.

2. Experimental investigation

The experiments were performed in this study through a pressure gun which consists of a reciprocating compressor, a pressure cylinder, an automated actuator valve, a smooth 1.5 m long barrel of 19.5 mm inner diameter, a 10 mm thick mild steel target mounting plate and a projectile catcher. The schematic arrangement has been shown in Fig. 1. The design pressure of pressure cylinder was 60 bar whereas the working pressure of actuator valve was 4 bar. The maximum velocity of the projectile was also increased with increase in length of the gun barrel. A high speed camera phantom V411 was employed to measure the impact as well as residual velocities of the projectile. EN-24 steel was used to manufacture the projectile which was hardened to Rockwell hardness Rc of 47–52 by oil quenching to minimize the plastic deformation of projectile during impact. The mass of the projectile was kept 0.0525 kg. Circular target plates of diameter 128, 160, 210, 260 and 315 mm were fixed to a thick mounting plate by means of 5 mm thick and 30 mm wide mild steel rings which contain equally spaced bolt holes (6 bolts for 128 mm and 8 bolts for 128, 160, 210, 260 and 315 mm outer diameter plates respectively). Thus the free span of aluminium plate was kept as 68, 100, 150, 200 and 255 mm as used in numerical study. Similarly to investigate the influence of configuration, two plates of 0.5 mm thick 150 mm free span diameter were kept in contact for layered in contact and kept 4.5 mm far for spaced target. The distance between two plates was maintained by keeping a 30 mm wide and 4.5 mm thick ring in between two 0.5 mm thin aluminium plates at the time of clamping. In each case the target was hit normally by hemispherical nosed projectile. To ensure the normal impact, the free flight distance between barrel out let and target plate kept very small, 50 mm. The barrel was smoothed and lubricated to reduce the friction between projectile and barrel internal surfaces. The trigger valve was pressed to launch the projectile. The projectile incidence velocity was varied by varying the pressure inside the cylinder through which the effect of impact velocity of the projectile on perforation mechanism, failure modes and ballistic resistance were studied and ballistic limit for different targets were obtained. After perforation, the projectile was recovered from a catcher positioned behind the target plate. The catcher was filled with cotton rag to avoid damaging the projectile.

3. Numerical investigation

The numerical simulations were carried out through a commercially available finite element code ABAQUS [19]. Projectile was modelled as rigid body and the target as deformable. To model the spaced target a predefined spacing was given between both the layers. Kinematic contact algorithm was used to simulate the contact between the target and projectile whereas the contact between two layers of the target was simulated by using general contact algorithm of ABAQUS [19]. During contact between projectile and the target, outer surface of the projectile was considered as master and the contact region of the target plate as node based slave surface whereas the contact between the contacting surfaces of layered in-contact as well as spaced target was modelled using rear surface of front layer as master surface and front surface of rear layer as the slave surface. The value of coefficient of friction between the contacting surfaces of layered in-contact target was considered as 0.5 [3]. For the spaced target with spacing of 4.5, 10 and 20 mm, the contacting surfaces come in contact for a very short duration, whereas the spaced target with higher spacing (30–60 mm), the contacting surfaces do not touch each other during perforation phenomenon. Similarly for 1 mm thick target the projectile and the target come in contact for a very short duration. Due to low thickness and short duration of contact the friction effect do not play significant role [15]. In the case of layered in-contact as well as spaced target the contact of projectile with both the layers was assigned. The clamped zone of target plate was restrained with respect to all degrees of freedom. Eight node brick elements (C3D8R) were considered in all the simulations carried out in present study. Because of large deformation of target, mesh was highly refined and aspect ratio was kept unity in the primary impact zone. The size of element in primary contact region of the plate was considered as 0.16 mm × 0.16 mm × 0.16 mm based on the mesh convergence study [2]. However the aspect ratios of elements were varied from 1 to 8 from centre to periphery region of the target to reduce the computational time. The detail of meshing has been shown in Fig. 2.

4. Material modelling of the target material

The material behaviour of 1100-H12 aluminium target against projectile impact has been modelled using Johnson-Cook elasto-visco-plastic material model [20,21] that is capable to correctly incorporate yielding, strain hardening, strain rate hardening, thermal softening and fracture of ductile materials. The equivalent von-Mises stress $\bar{\sigma}$ and equivalent fracture strain $\bar{\varepsilon}^{pl}{}_{f}$ of the Johnson-Cook model are expressed as;