Numerical Study on Failure Process of AL2024 T3 Plate under Normal Impact by Ogival Projectiles

Mohd Norihan Ibrahim, Waluyo Adi Siswanto, and Ahmad Mujahid Ahmad Zaidi

***Abstract*—**The present study is concerns about numerical analysis on failure process of deformable aluminium target plate perforated by rigid ogival projectile nose shape. The perforation process has been simulated by the application of 3D analysis using IMPACT dynamic FE program suite. The comparison on failure modes by ogival projectile nose shape have been studied and evaluated. The study covered different failure modes including perforation, petalling and holes expansion of perforated aluminium sheet according to different level of impact velocities. A wide range of impact velocities from 100 m/s to 600 m/s has been covered in the tests. The projectile has the diameter of 22 mm and the aluminium circular sheet has the diameter of 50 mm. Different failure modes for each case was found. For the velocity impact of 100 m/s dishing and petalling formation observed while for higher impact velocity (≥ 300 m/s) extensive petal formation modes of failure generated. Good agreement is obtained between simulation using IMPACT explicit and ABAQUS explicit finite element code analysis.

***Keywords*—**Finite element method, Projectile impact, Perforation, Failure mode

I. Introduction

PERFORATION of plates during projectile impact is a complex process, normally involving large elastic and plastic deformation, high stress and strain rate, crack formation, dishing, petal formation, plugging and fragmentation. The perforation is dominated by the local penetration although the failure mechanism of the final perforation also influences the ballistic limit of a thick target, which depends on the target material, target dimensions, projectile nose and impact velocity. Petalling is the most frequent phenomenon in thin aluminium plates when impacted by ogive nosed and spherical projectiles at medium and high velocity impact. Iqbal et al. [1] performed three dimensional numerical simulations to study the effect of projectile nose shape on the ballistic resistance of ductile targets. 1mm thick of 1100-H12 aluminium target was impacted by 19 mm diameter projectile with varying calibre radius head (0 - 2.5). The ballistic limit of 1 mm thick aluminium target was affected significantly by the calibre radius head of projectile.

A relevant literature dealing with high strain rate behaviour of metallic materials impacted by projectile of different projectile nose were investigated by several researchers [2, 3]. The deformation and the damage development in the target are relevant phenomena which should be considered when assessing the performance of aluminium sheets against impact loading. A three dimensional model is developed in LS-DYNA/explicit to simulate the perforation of steel and aluminium target using a Modified Johnson Cook model [4]. The numerical results show good correlation with the published experimental results and the study demonstrates that the material model is able to emulate failure characteristics of the steel and aluminium plates as observed in various experimental observations.

An analytical perforation model based on the cylindrical cavity expansion has been reformulated and used to calculate the ballistic perforation of resistance of the aluminium plates [5]. The target material was modelled with the modified Johnson and Cook constitutive relation. The physical behaviour of the target during perforation is well captured in the FE simulations when the model is used. Dean et al. [6] study on the energy absorption in thin steel plates during perforation by spherical projectiles of hardened steel at impact velocities between 200 and 600 m/s. The tests were simulated using ABAQUS explicit finite element code and using Johnson Cook plasticity model. Good agreement is obtained between simulation and experiment and the model successfully captures the transitions in failure mode as projectile velocity increases.

The current paper presents the results of numerical investigation undertaken to study the perforation process of circular shape of target plate when subjected to the impact by different projectile nose shape at different velocity. In this investigation, the analysis of process requires the following assumptions: (a) The amount of energy absorbed by the projectile is neglected, (b) The projectile move with the same velocity after the initiation of perforation, (c) The plastic deformation is taken into account in the target plate while elastic deformation is neglected, and (d) The strain rate effect of the material is considered. The perforation capabilities of projectile against constraints plates were explored for an efficient damage and failure modes.

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II. Numerical Modelling

A. *Finite Element Model*

The proposed finite element models of projectiles are shown in Fig. 1. The projectile has the diameter of 22 mm and the circular shape of target plate has the diameter of 50 mm and 2 mm thickness. Both projectiles and target plate is modelled using finite element pre-processor GiD with IMPACT interface module. The circular plate is constrained around the edges and subjected to impact by a projectile with different velocities. The projectile is modelled as contact triangle (CT) elements. Both the target plate and the projectiles are modelled in full so as to be able to simulate the failure mode in target plate from the point of impact towards the constraints edge and back. A 3D finite element model for the simulation of the penetration process was developed in IMPACT explicit finite element program suite.

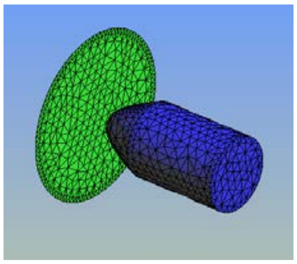

Fig. 1 Finite element model of ogival projectile and target plate

The ability of the application programs in dealing with contact algorithms provide a powerful platform to simulate several types of armour target subjected to the impact of projectiles moving at various velocities [7]. The circular target plate is considered as deformable body and represented by the element mesh defined by triangle elements with the element mesh generated equal to 2.5. The elements, name as SHELL _C0_3 is three node shell elements based on the classical C0 formulation by Belytschko et al. [8]. The projectile is assumed as a rigid body and is categorized as contact triangle element. This assumption reduces the computational time required for the simulation.

Table 1
Material Properties Of Target Plate

Type of material	Aluminium 2024 T3
Property of material	Elastoplastic
Young modulus, E	73.08 GPa
Poisson ratio, ν	0.33
Mass density, ρ	2700 kg/m^3
Thickness of plate, t	2 mm
Integration point	5
Yield stress, σ_y	0.35 GPa
Hardening factor	0.1
Contact type	Basic
Contact factor	10.00
Contact friction	0.25
Type of failure	Failure strain = 0.50

An aluminium 2024 T3 is used as a material model of circular target plate. Aluminium 2024 T3 is a strain rate dependent isotropic elastic plastic model. The material properties of aluminium 2024 T3 is shown in Table 1. The material model in IMPACT dynamic FE program suite, aluminium 2024 T3 is examined for its suitability in simulating target plate under dynamic impact loading.

B. *Constitutive Relation*

In a mathematical description of material behaviour, the response of the material is categorized by a constitutive equation which gives the stress as a function of the deformation history of the body. The impact between projectile and target plate involve the development of permanent strain called plastic materials. A theory of contact deformation can be used to relate normal contact force to deformation and subsequently to relate deformation to work done on the contact region by the normal force of colliding bodies.

In this research, a rigid 3-dimensional of ogival projectile colliding against an elastic-plastic target plate and a nonlinear explicit 3-dimensional finite element program, IMPACT used to analyze the problem. In the elastic-plastic contact, the transition between perfectly-elastic and fully-plastic behaviour can be based on the stress field due to expansion of a cylindrical or spherical cavity in an elastic-plastic solid [8]. The half-space contains a hydrostatic core of radius a that is surrounded by a cylindrical elastic-plastic shell of outer radius which is centred at the initial point of contact. By performing an appropriate analysis, the mean contact pressure is obtained for the cylindrical cavity model as

$$\frac{p}{\sigma_y} = \frac{2}{3} + \frac{1}{\sqrt{3}}\left[\frac{4}{3\pi}\frac{Ea}{\sigma_y^2}\right] \tag{1}$$

where p is the mean or average contact pressure, σ_y is the yield stress, E is the Young's Modulus, a is the contact patch and R is the radius of curvature. Through the process of substitution and evaluation on equation (1), the normal force F may be expressed as

$$\frac{F}{F_y} = \frac{a}{a_y}\left(1 + \frac{2}{3\sqrt{3}}\ln\frac{a}{a_y}\right) \tag{2}$$

the compliance relation for the elastic-plastic indentation during compressive stage of impact may be obtained as

$$\frac{F}{F_y} = \left[\frac{\delta_y}{\delta_y^2}\left(\frac{\delta}{\delta_y} - 1\right) + 1\right]^{1/2}\left\{1 + \frac{1}{3\sqrt{3}}\ln\left[\frac{\delta_y R}{a_y^2}\left(\frac{\delta}{\delta_y} - 1\right) + 1\right]\right\} \tag{3}$$

The Lagrangian formulation is adopted to formulate the material constitutive relationship for dynamical characterization and deformation of target plate. Belytschko et al. [9] reported that the Lagrangian finite elements prove extremely useful in large deformation problems in solid mechanics and are most widely used in solid mechanics. The formulations apply to large deformations and nonlinear materials where they consider both geometric and material nonlinearities.

C. *Failure Criterion*

The application of failure criterion on the material deformation behaviour is widely accepted in the analysis of metallic structure subject to dynamic loading [3]. The material failure is defined by a constant value of the equivalent plastic strain. Since the target is very thin, the stress field across the thickness of the plate is nearly constant during the perforation process where the pressure along the projectile and plate interaction is constant. The value of failure strain adopted in the simulations, f = 0.50, which is estimated from the experimental observations of the material deformation behaviour. This value is slightly higher than the corresponding to the necking strain under dynamic loading [3]. The process of strain localization and necking formation that cause perforation of target plate is sufficiently defines in the finite element simulation. It is noted that the failure criterion applied involves deletion of elements. The elimination of elements during FE analysis is restricted to the crack propagation stage during projectile –target interaction

III. Result And Discussion

The failure process of aluminium plate subjected to normal impact by ogival projectile nose shape was examined. There are several parameters affect the deformation and penetration of aluminium target plate when subjected to the impact by a projectile. Some of these parameters are the penetration process, petalling process, velocity impact, stress and strain rate effect and holes expansion.

A. *Petalling Process Analysis*

The beginning of the petalling process during perforation is always associated with fracture initiation and the outward move of petals as perforation continues as shown in Fig. 2(b) and Fig. 2(c) respectively. At the time step, t= 90 μs, dishing formation occurs and the following motion of projectile leads to the crack propagation of the impacted surface and initial stage of perforation occurs at the speed of 150 μs. At the time step, t = 300 μs half of the projectile body pass through the perforated surface and the petal formation generated around it a2 shown in Fig. 2(d). The petals generated in forms of uniform triangular cross section and some in forms of trapezoidal shape. When the time step reach at t = 690 μs, the projectile is exiting the perforated surface and through the observation made, there are five petals generated. According to the profile of petalling observed, the final form of the petal bending can be considered as a triangular cross section for ogival projectile impact as shown in Fig. 2(e). As the projectile passing through the perforated thin plate, this stage is considered as projectile exit and the deform shape of the shell will remain in its state. According to the results shown, the generation on the number of petal and the failure mode is significantly influenced by the projectile nose shape.

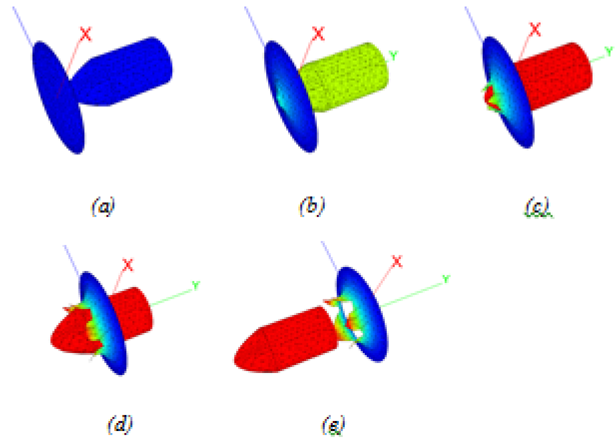

Fig. 2 Numerical results of ogival projectile configuration. The profile and pattern of circular sheet during pre and post perforation at velocity, v = *100 m/s.*

B. *Influence of Impact Velocity*

The next parts of the papers are detailed analysis of impact and deformation at different level of velocity towards target behaviour. Numerical simulation were carried out to study the response of 2 mm thick 2024 T3 aluminium target plate subjected to normal impact of projectile. Each projectile was impacted at different velocity in order to obtain the target profile and failure mode configuration. The number of radial crack increases with the increase of impact velocity. This phenomenon is induced by the increase of circumferential strain level responsible of the crack initiation and progression [10, 11]. Fig. 3 shows the failure mode of ogival projectile shape struck the circular target plate at impact velocities of 100 m/s, 300 m/s and 600 m/s respectively.

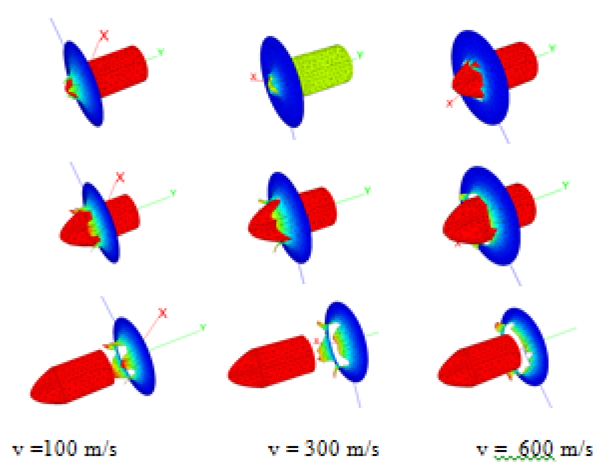

Fig. 3 Failure mode configuration of impacted target plate by different velocity impact of ogival shape of projectile

There are three phase of perforation process representing each of the velocity impact arranged in vertical position. The first phase indicates an initial deformation and early crack propagation characteristics of circular aluminium target plate. The second phase shows the half way perforation process and impact response while the third phase shows the rigid body projectile exit. The initial stage of impact leads to the dishing formation of circular plate at the velocity of 100 m/s and smaller size of dishing occur for the impact velocity of 300 m/s and 600 m/s respectively.

An obvious deformation and failure mode may be observed clearly in the third stage of projectile – target perforation where the opening of petals is greater for higher impact interaction and the other effect is on the hole expansion where the perforation at the speed of 300 m/s and 600 m/s contribute significantly on the hole enlargement. This is due to the large forced imposed on the impacted surface area.

C. Hole Enlargement

The effects of velocity on the enlargement of hole after impact are shown in Fig. 4. The images shows the post perforation of ogival shape of projectile impacting circular target plate at the velocity ranging from 100 m/s, 300 m/s and 600 m/s respectively. The top images in row in Fig. 4 indicate three dimensional of perforated target plate while the bottom images in row represent denoted as (d), (e) and (f) indicates the size of hole enlargement and the gap between projectile and perforated target plate. The failure modes obtained for the impacted target plate vary in terms of crack propagation, petal formation and the size of holes expansion. The enlargement of hole keeps increasing as the increase of velocity impact. At the velocity of 600 m/s the enlargement of holes increases, multiple cracks perforation exists and reduction on the size of petals.

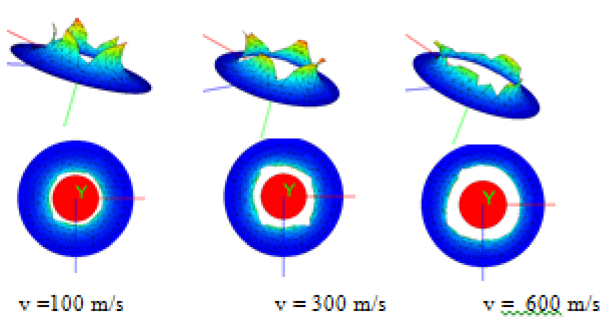

Fig. 4 Holes enlargement due to the effect of velocity impact

D. Local Strain(I) Effect

Fig. 5 shows three dimensional post penetration of the impacted circular target plate. It is shown that several numbers of petals formed around the perforated surface. The local strain contour has been plotted in Fig. 5(c). Through the images shown, it is absolutely indicated that the perforated target region shows different tone of strain level. The highest strain is labelled with red colour and its colour tone decreasing as the strain level decreases. The portion of the target plate that was in contact with the projectile bent in the shape of projectile and crack apart to form petals. Through the images plotted, the maximum strain effect occurs when the plastic deformation takes place and the deformed surface start form initial crack propagation. The local strain reach the maximum level at 0.4996 (denoted with dark red) and it does occur at the time step between 23 μs to 40 μs.

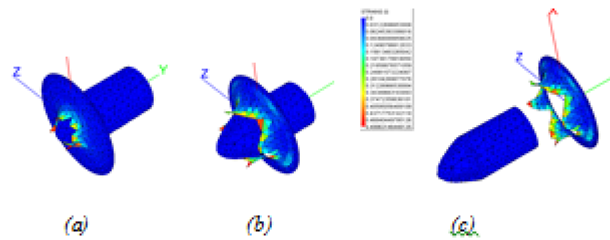

Fig. 5 Failure mode contour profile for ogival projectile shape impacting circular sheet at the velocity, *v* =300 m/s

IV. Comparison Of Result

Fig. 6 shows the failure modes contour plot for the impact between ogival projectile and thin target plate. Fig. 6(a) shows the failure modes obtained by ogival projectile impacting thin aluminum 2024 T3 at the velocity of 150 m/s. The projectile has the diameter of 22 mm while the circular plate has the diameter of 50 mm. From the numerical simulations, the failure modes observed are the formation of petals and the number of petals equal to five.

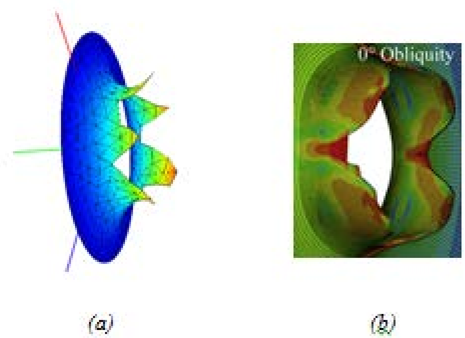

Fig. 6 Failure modes contour plots of the perforation process by ogival nose projectile impact, (a)Numerical by IMPACT (AL2024 T3); (b) Numerical by ABAQUS (AL1102 H12)

In order to verify on the profile of failures, the similar geometry and dimensions of projectile and target plate was done by Iqbal et al. [1] as shown in Fig. 6(b) where the material used is made of aluminum 1100 H12. ABAQUS/Explicit finite element code was used to carry out the numerical simulation. Based on the analysis carried out, necking, radial cracking and petals formation are observed for the numerical result for both IMPACT and ABAQUS Explicit FE software. The different is on the number of petals where numerical simulation using ABAQUS form four petals while IMPACT form five petals. Small gap or different occur due to the size of meshing for both simulation. Anyway the basic shape and formation of petals are in a good agreement between both of simulations.

V. Conclusion

A numerical investigation has been carried out to analyze in details the perforation process of target plate when subjected to normal impact by ogival nose shape of projectile.

Numerical simulations have been performed using IMPACT/Explicit finite element code. The impact region of circular target plate is significantly affected by the projectile nose shape. The failure mechanism of the plates impacted by ogival nose projectile was the formation of petals around the perforated surface. The numbers of petal formation increases as the impact velocity increases but reduced in it size. At the velocity of v = 100 m/s, the impacted surface by ogival nose projectile form four petals while at v = 300 m/s, five petals were generated. At v = 600 m/s, seven petals formed and its size reduced. The increases of impact velocity contribute positively on the holes enlargement of perforated surface. As a result, the gap between the projectile and the target also increased. The occurrence of holes expansion or enlargement is proportional with the increment of impact velocity. It can be concluded that the model succeeds in defining failure mechanisms associated with the configuration of projectile – target. This reinforces the hypothesis regarding the applicability of the failure criterion to capture the main aspects of the perforation process of target plate impacted by several type of projectile nose shape. Good agreement is obtained between numerical simulation by IMPACT explicit and ABAQUS explicit finite element code. Thus it can be concluded that the failure mode of impacted target plate is influenced significantly by the projectile nose shape.

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