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Perforation mechanics of 2024 aluminium protective plates subjected to impact by different nose shapes of projectiles

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ABSTRACT

This paper focuses on the mechanical behaviour of aluminium alloy 2024-T351 under impact loading. This study has been carried out combining experimental and numerical techniques. Firstly, experimental impact tests were conducted on plates of 4 mm of thickness covering impact velocities from 50 m/s to 200 m/s and varying the stress state through the projectile nose shape: conical, hemispherical and blunt. The mechanisms behind the perforation process were studied depending on the projectile configuration used by analyzing the associated failure modes and post-mortem deflection. Secondly, a numerical study of the mechanical behaviour of aluminium alloy 2024-T351 under impact loading was conducted. To this end, a three-dimensional model was developed in the finite element solver ABAQUS/Explicit. This model combines Lagrangian elements with Smoothed Particle Hydrodynamics (SPH) elements. A good correlation was obtained between numerical and experimental results in terms of residual and ballistic limit velocities.

1. Introduction

The impact-protective capacity of structural components has become a relevant requirement for the automotive and aerospace industries. Both energy absorption and crashworthiness concepts are essential for the development of new vehicles and aircraft. In such applications, design challenges are focused on structural crashworthiness and light-weight vehicles. Accordingly, research on crashworthiness has managed to considerably reduce fatalities by 26% in the USA from 2005 to 2011 [1].

Several studies have been carried out to study the impact behaviour of metallic plates. In this field, the research developed by Borvik and co-authors [2–4] and Gupta and co-authors [5,6] can be highlighted because of their relevance. Their work focused on mechanical variables that govern the penetration process, such as the target material, target dimensions, projectile nose shape and impact velocity. In this regard, the projectile-nose determines the stress state and its effect varies with several parameters such as the thickness of the target plate, impact velocity, target thickness to projectile diameter ratio and nose angle or nose radius of the projectiles [7–12]. However, there still remains a need for a systematic study of the influence of projectile nose shape on global deformations (plate deflection, bending and membrane stretching) and local deformations (ductile hole formation, petalling, plugging, rear bulging, discing, tensile tearing, thinning, shear banding and necking) of aluminium plates under impact loading. The study of energy absorption capacity on metallic plates can provide relevant information on the effects of local impacts on the global structural response. This work focuses on the perforation process of a ductile plate of AA2024-T3 when it is subjected to an impact of a non-deformable projectile. To the authors' knowledge, none of the previous impact and perforation studies of AA2024-T3 investigated the effect of the projectile shape on the material response, while keeping the same kinetic energy and boundary conditions. The new experimental data of residual velocities for AA2024-T3 presented in this study can be very useful and relevant especially for the design and optimization of protective structures.

Finite Element Method (FEM) has been commonly used to simulate impact problems. This method provides models that predict residual velocities, ballistic limits and failure mechanisms depending on the projectile-target configurations [13–18]. Most of the previous studies did not focus on quantifying the amount of global and local energy absorption during the impact process. A common problem in FEM is the excessive element distortions encountered in dynamic loading simulations [19]. Element deletion approach could be used to erode highly

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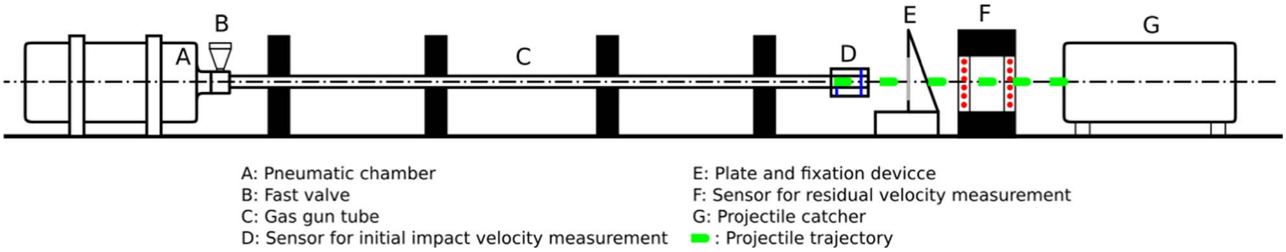

Fig. 1. Scheme of experimental set up used for perforation test.

distorted elements but presents inconsistencies and no physical fundamentals [20]. In order to minimize this problem, several authors [21,22] described the advantage of using adaptive meshing algorithm as an alternative technique for the analysis of plate-impact events. The scheme of the adaptive mesh available in some commercial FE software (e.g., ABAQUS [23]) combines the features of Lagrangian and Eulerian analyses which allows for obtaining a high mesh quality during the whole simulation. However, the adaptive remeshing technique is computationally expensive and can lead to numerical instabilities and unexpected termination of the simulation [24]. A mesh-free Smoothed Particle Hydrodynamics (SPH) technique presents several advantages over conventional FEM and can be also used for impact problems [25]. This avoids extreme mesh distortions in problems that involve impact and penetration. However, SPH technique encounters several difficulties in engineering problems such as tensile instability; difficulty in loading essential boundary condition and high computational cost. A new computational method has been recently proposed to fill the gap between conventional FEM and models based on SPH. This method is based on a Lagragian mesh whose elements are converted into SPH elements when a *conversion variable* (strain, stress or any state variable) reaches a critical value. By this way, some distortion- and instability-related problems are avoided without introducing a too expensive computational cost. This approach assumes a rigid coupling between SPH particles and Lagrangian nodes at the interface zone [22,25–27]. The rigid interface definition, however, induces some problems, particularly at highly localised regions as discussed in detail by Zhang and co-authors [26]. This novel approach has been used to simulate high velocity impact computations [28], and is employed in this work for the numerical analysis. In addition to the advantages mentioned above, this method allows also for retaining the mass and mechanical properties of the elements converted into SPH particles.

The main objective of this research is the analysis of failure mechanisms of aluminium alloy 2024-T531 plates perforated by rigid projectiles of different nose shapes. Perforation tests were conducted using conical, hemispherical and blunt projectiles covering impact velocities from 50 m/s to 200 m/s. The experimental arrangement enables the determination of the impact velocity, the residual velocity and the failure mode of the aluminium plates. The experimental results were used to validate and identify the value of the mechanical variable that controls the conversion FEM- SPH method. Once the numerical model was validated with experimental data, it was used to analyze energy absorption mechanisms associated with the deformation and failure of the aluminium plates. In addition, both experimental and numerical techniques allowed for investigating the influence of impact velocity, target thickness and projectile nose shape on the failure mechanisms. The outcomes of this work provide new insights into the energy absorption and failure mechanisms behind the perforation process of AA2024 which allow for a better comprehension of its mechanical response under different impact conditions. The results presented herein provide new relevant information for the design of structures potentially subjected to impact loading such as aeronautical components.

2. Experimental program

2.1. Material

In the present investigation, the attention is focused on the mechanical behaviour of aluminium alloy (AA) 2024-T351. The principal applications of this material are aircraft structural components, wing tension members, hardware, truck wheels, scientific instruments, veterinary and orthopaedic braces and equipment, and in rivets because of its high strength, excellent fatigue resistance and good strength-to-weight ratio. The AA 2024 T-351 has been widely studied in terms of mechanical behaviour as well as ductile failure (see a previous work of Rodríguez-Millán and co-authors [29]), but its mechanical behaviour against impact loading has not been analysed enough. Prior to conducting the impact tests, some experiments were conducted under quasi-static conditions in order to verify the material used and its similarities with the one employed in previous published studies (see Appendix A).

2.2. Test set-up

Perforation tests were conducted using a pneumatic gas gun to launch a projectile onto an AA 2024-T351 plate specimen, see Fig. 1. The maximum velocity of the projectile, denoted as *impact velocity Vo*, is reached at the end of the tube C. Both initial impact and residual velocities of the projectiles were measured during the impact tests using laser sensors attached to photodiodes and timers at D and F. The maximum error on the velocity measurements between the two sensors was estimated around $\Delta\overline{V} \approx 1m/s$. Further details of the experimental setup are provided in previous works [10,12]. In addition, the set-up E may be instrumented to measure the force impact or force perforation on time as reported in [40] using four piezoelectric sensors with a maximum force of 80 kN.

The AA 2024-T351 specimens were clamped along four edges using a rigid support in order to reduce sliding effects during the test. This arrangement (screwing + clamping) has been discussed in previous works by the authors [10,11]. The active target area of the specimens was reduced to $100mm \times 100mm$ with a plate thickness of 4 mm, see Fig. 2.

The tests were conducted using three types of projectiles released at different impact velocities up to $V_0 \approx 200m/s$: The projectiles were made of a maraging steel with a heat treatment to reach a yield stress close to $\overline{\sigma}_y = 2GPa$. The projectiles, independently of the nose shape configuration, present a maximum diameter $\phi_{projectiles} = 13mm$ and a constant mass of $M_p \approx 30g$. Their geometries and dimensions are shown in Fig. 3-a-c.

The diameter of the projectiles was approximately equal to the diameter of the barrel to ensure a perpendicular impact on the aluminium plate.