Perforation Analysis of the Aluminum Alloy Sheets Subjected to High Rate of Loading and Heated Using Thermal Chamber: Experimental and Numerical Approach

A. Bendarma, T. Jankowiak, A. Rusinek, T. Lodygowski, M. Klósak, S. Bouslikhane

***Abstract*—**The analysis of the mechanical characteristics and dynamic behavior of aluminum alloy sheet due to perforation tests based on the experimental tests coupled with the numerical simulation is presented. The impact problems (penetration and perforation) of the metallic plates have been of interest for a long time. Experimental, analytical as well as numerical studies have been carried out to analyze in details the perforation process. Based on these approaches, the ballistic properties of the material have been studied. The initial and residual velocities laser sensor is used during experiments to obtain the ballistic curve and the ballistic limit. The energy balance is also reported together with the energy absorbed by the aluminum including the ballistic curve and ballistic limit. The high speed camera helps to estimate the failure time and to calculate the impact force. A wide range of initial impact velocities from 40 up to 180 m/s has been covered during the tests. The mass of the conical nose shaped projectile is 28 g, its diameter is 12 mm, and the thickness of the aluminum sheet is equal to 1.0 mm. The ABAQUS/Explicit finite element code has been used to simulate the perforation processes. The comparison of the ballistic curve was obtained numerically and was verified experimentally, and the failure patterns are presented using the optimal mesh densities which provide the stability of the results. A good agreement of the numerical and experimental results is observed.

***Keywords*—**Aluminum alloy, ballistic behavior, failure criterion, numerical simulation.

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I. Introduction

THE aluminum alloy 1050 is a popular grade of aluminum for general sheet metal works where moderate strength is required. Alloy 1050 is known for its excellent corrosion resistance, high ductility, and highly reflective finish. This aluminum alloy is one of the best alloys in the market, as it is the most economical and conductive alloy in the 1000 series. Due to the lack of perforation analysis researches on this aluminum alloy, we decided to make it the subject of our work to exploit its excellent properties in the fields which requires this type of characteristics [1].

TABLE I
CHEMICAL COMPOSITIONS PROPERTIES OF ALUMINUM ALLOYS

Chemical composition in%							
0.40	0.25	0.07	0.005	0.05	0.05	0.05	Bal

TABLE II
MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

Proof Stress (MPa)	Tensile Strength (MPa)	Hardness Brinell	Elongation A (%)
85	105-145	34	12

An analytical model has been proposed by Atkins and Liu [2] to define the necking and the number of radial cracks formed during perforation while using different shapes of projectiles on ductile materials. The penetration of hemispherical nose projectile on laminated aluminum was studied by Alavi and Hoseini [3] and it resulted in a mixture of failure modes. Borvik et al. [4], Kpenyigba et al. [5], Rusinek et al. [6], and Backman and Goldsmith [7] reviewed the perforation of projectiles into target and they concluded that the projectile's nose shape considerably affects both the target's energy absorption mechanism and the failure mode during penetration.

The Johnson-Cook constitutive model (JC) is the most frequently used model and is accurate for many applications [8]. The JC relation is expected to be very popular due to its simplicity of application and calibration. Johnson and Holmquist [9] considered the influence of a modified Johnson-Cook constitutive relation using numerical simulations of steel plate perforation.

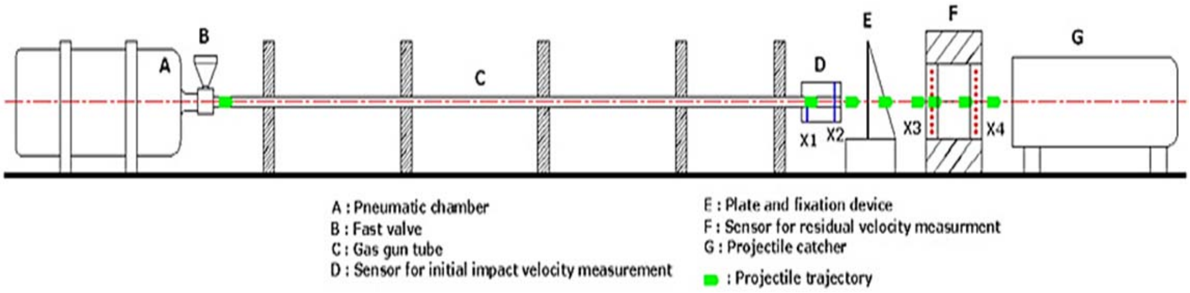

Fig. 1 Experimental device presentation

This paper puts the importance on experimental ballistic impact coupling with a significant information on numerical simulations than that usually observed. Different effects are mixed including the shapes and the mass of the projectiles, the thickness of the sheet, and the behavior of the material. For this reason, it is difficult to interpret how these parameters affect the results.

II. Experimental Research Methodology for Perforation

A. Set-Up Description

This part describes the mechanical behavior of aluminum sheets under impact loading. Experimental, analytical, and numerical investigations have been conducted to analyze in details the perforation process [5]. During experimental tests, the aluminum sheets have been impacted by a rigid projectile. The mechanical part of the experimental setup is shown in Fig. 1. The projectile is launched using a pneumatic gas gun; it accelerates in the tube C to reach the initial impact velocity V_0. Then, the projectile impacts the aluminum sheet with partial or complete perforation depending on the quantity of kinetic energy delivered to the material tested [5].

The dimensions of the plates used during experiments are given in Fig. 2. The active part is 100 x 100 mm^2, the thickness is 1 mm and it is embedded on a rigid support allowing to reduce sliding effect during the test. The plate has been impacted by the projectile in the central zone as shown in Fig. 2. A wide range of initial impact velocities was considered for a complete definition of the ballistic curve of the aluminum sheet, $35 \le V_0 \le 180$ m/s.

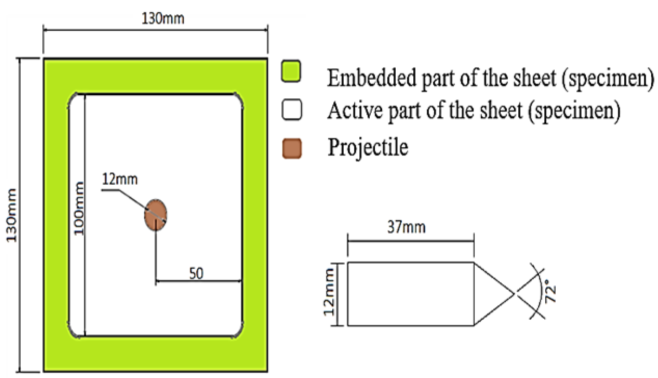

Fig. 2 Geometry of aluminum plate used during perforation tests, thickness 1 mm, and projectile shape

B. Experimental Results

In this study, a conical projectile shape (Fig. 2) has been used to analyze the effect on the ballistic curve V_R - V_0. The projectile mass is kept constant, Mp=28 g. The material used for machining the projectile is maraging steel with the heat treatment to achieve a yield stress of projectile equal to 2 GPa. Therefore, the projectile may be assumed rigid during the perforation process [10]. The results in terms of ballistic curve $V_R - V_0$ are presented in Fig. 3.

The residual velocity of the projectile can be calculated using the following equation proposed by Ipson and Recht [11]:

$$V_R = (V_0{}^{\kappa} - V_B{}^{\kappa})^{1/\kappa}, \tag{1}$$

where V_0 is the initial velocity, and V_B is the ballistic velocity. In the above equation, the constants V_B is equal to 40 m/s, and κ is the ballistic curve shape parameter.

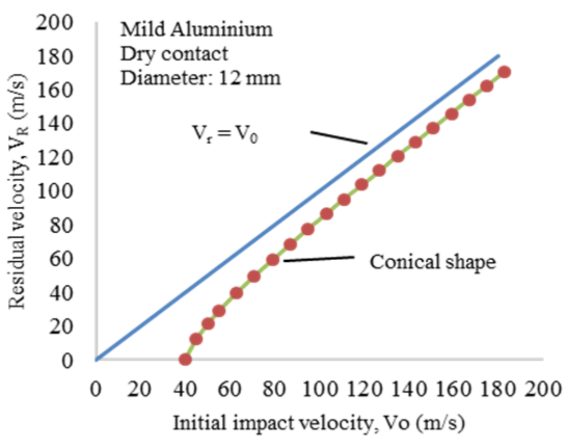

Fig. 3 Ballistic curve obtained during perforation and determination of the ballistic limit

The energy absorbed by the plate E_d can be calculated using:

$$E_d = \frac{m_P}{2}\left(V_0{}^2 - V_R{}^2\right) \tag{2}$$

The difference of the initial and residual kinetic energy can be calculated using the experimental data, then based on the Recht-Ipson approximation, the energy absorbed by the plate can be calculated (see Fig. 4). Using (2)

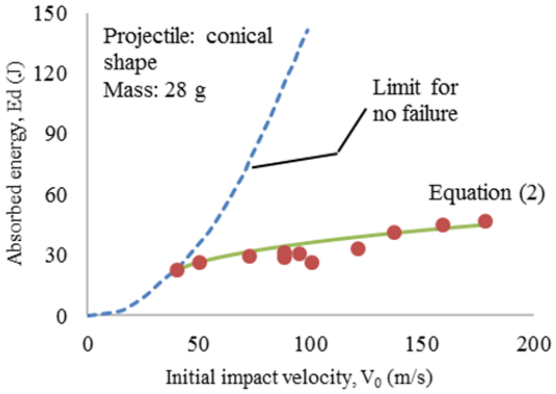

Fig. 4 Energy absorbed by the plate during impact test, determination of the failure energy

Analytical predictions discussed in [12] are fully confirmed for room temperature, whereas more discrepancy in petals number is reported at higher temperatures. Petals up to five are observed for impact velocities at the highest predefined temperatures. The exemplar failure modes are presented in Fig. 5.

(a) (b)

Fig. 5 Experimental observations of petaling failure mode, (a) four petals at T=20˚C and V_0=120 m/s, (b) five petals at T=260 ˚C and V_0=101 m/s

III. Numerical Simulation of the Perforation Process

In this section, the numerical modeling methodology is presented. The numerical model and the description of both initial and boundary conditions are described. In addition, the constitutive relation of the material together with the failure criterion are reported. The numerical results are also included and are compared with experimental data.

In order to perform the numerical approach of the perforation process, a parametric study of the AL1050 aluminum alloy has been made, using the Johnson-Cook model as the constitutive law.

The constitutive relation (JC) investigated is described by various authors, and it is implemented in commercial finite element codes such as ABAQUS.

The explicit formulation of the JC thermoviscoplastic model is defined as follows:

$$\sigma = (A + B\varepsilon^n)\left[1 + C\,.Ln\,\frac{\dot{\varepsilon}}{\varepsilon_0}\right][1 - (T^*)^m] \quad (3)$$

where **A** is the yield stress, **B** is the constant of the material, **n** is the hardening coefficient, **C** is the strain rate sensitivity coefficient and m is the temperature sensitivity. To define the thermal softening of the material studied during dynamic loading.

The non-dimensional temperature T^* for the temperature in range between T_0 and T_m is defined in the following form:

$$T^* = \frac{T - T_0}{T_m - T_0} \quad (4)$$

A. Numerical Approach

The optimal mesh has been obtained using a convergence method (stability of the results without mesh dependency). The mesh is denser in the projectile-plate contact zone, the thickness of the plate in this area is 1.0 mm and the velocity is defined in the predefined fields with the range of impact velocities from 35 to 180 m/s as conceded in the experiment. This model contains 6224 elements in the central part of impact and 6381 using the same element size (0.4 x 0.4 mm).

The ballistic curves are reported in the following section and compared to the experimental results. The interior zone of the model allows to initiate the process of crack propagation in a precise way.

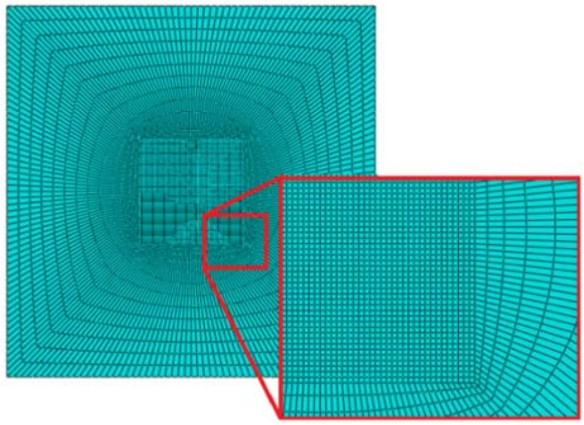

Fig. 6 Numerical model used during numerical simulations (mesh density distribution)

A decrease of the number of petals with a nose angle of 72° has been observed when the value of the failure strain is changed. An analytical model for the number of petals prediction proposed by Atkins et al. [2] has been used and confirmed by FE simulations. As it is shown in Fig. 8 the number of petals is the same as in the experiments, four petals are observed. It was reported in [2], [12] that the number of petals N observed during dynamic perforation coupled to a conical projectile shape was related to the nose angle ϕ.

B. Results Comparison

The plots clearly showed that the numerical model reproduces qualitatively the overall physical behavior of the plate during penetration and perforation. For complete authentication of the numerical model, the ballistic curves are plotted based on the numerical result and compared with those obtained experimentally.

International Science Index, Materials and Metallurgical Engineering Vol:11, No:4, 2017 waset.org/Publication/10006944

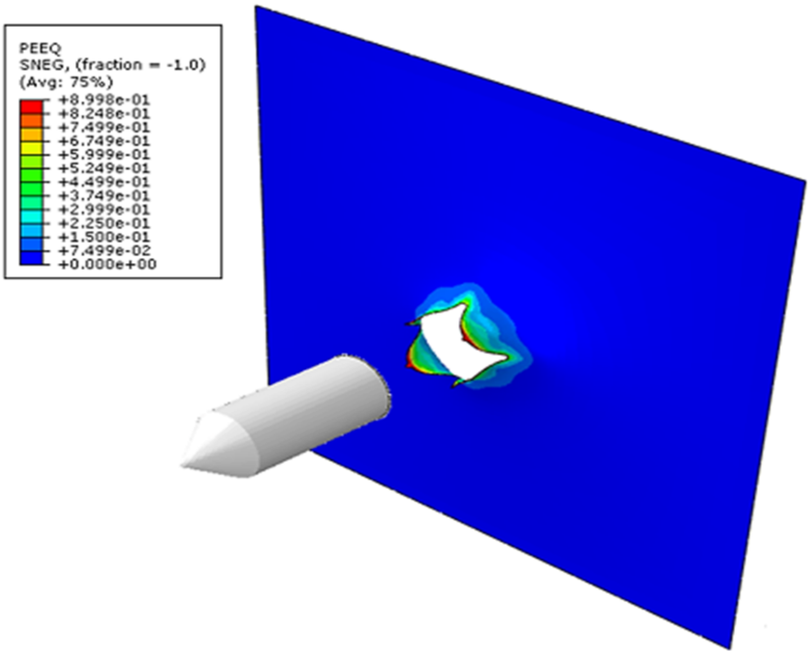

Fig. 7 Equivalent plastic strain distribution for macroscopic strain ε

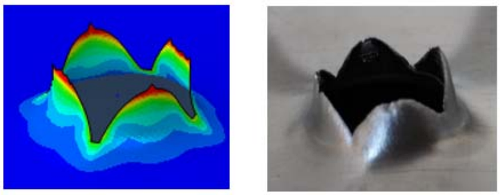

Fig. 8 Numerical result for conical projectile shape, V0=120 m/s, comparison between experiments and simulations

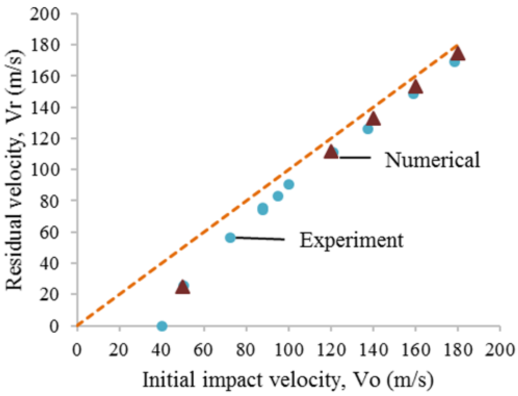

Fig. 9 The ballistic curve in experiment and in simulation

IV. Conclusion

The paper describes the mechanical behavior of brass alloy under impact loading. The work is focused on perforation tests carried out at wide range of velocity. Based on this experimental series, the ballistic properties of the material impacted by conical nose shape projectile are studied. The experimental investigations have been extended by numerical simulations using a general purpose software ABAQUS/ Explicit. The phenomenological constitutive relation has been checked coupling with a failure criterion. Finally, good correlation is reached between numerical and experimental results.

Acknowledgment

This research was partially supported by Poznan University of Technology and the International University of Agadir. We thank our colleagues from National Engineering School of Metz (ENIM) who provided insight and expertise that greatly assisted the research.

We would also like to show our gratitude to T. Lodygowski for sharing his pearls of wisdom with us during the course of this research.

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"Experimental and numerical analysis of the aluminum alloy sheet subjected to impact and perforation process –" in the 6th International Symposium on Aircraft Materials in Agadir-Morocco and **"Evolution Of Tenacity In Mixed Mode Fracture -Volumetric Approach-"** in the 6th International Symposium on Aircraft Materials and **"Experimental and Numerical Analysis of Perforation Process for Selected Aluminum Alloys - Defining Friction Coefficient and Failure Criterion"** in Engineering Mechanics Institute Conference 2016 in Nashville- USA.