# Experimental and numerical study of aluminum alloy specimens subjected to high rates of loading during perforation tests and heated using high-performance thermal chamber

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## 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 work is focused on perforation tests carried out at a wide range of specimen temperatures. This has been obtained by using the specially designed thermal chamber to heat specimens before impact. Based on this experimental series, the ballistic properties of the material impacted by a conical nose shape projectile are studied. The experimental investigations have been extended by numerical simulations using a general purpose software Abaqus/Explicit. The constitutive relation has been checked and coupled with a failure criterion. Finally, good correlation is reached between numerical and experimental results.

**Keyword:** *aluminum alloy, high rates of loading, perforation test, high-performance thermal chamber.*

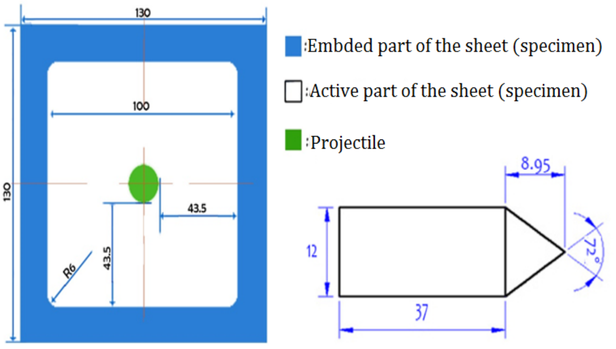
## 1. Introduction

The impact problems (penetration and perforation) of metallic plates have long been of interest. Several studies related to this subject are available in international literature. Atkins et al. [1], Borvik et al. [2] and Kpenyigba et al. [3] and Rusinek et al. [4]. Backman et al. [5] reviewed the perforation of projectiles into target and proposed an analytical model for ballistic velocities based on damage mechanisms. Kpenyigba et al. [3] and Rusinek et al. [6] studied the influence of the projectile nose shape (conical, blunt and hemispherical) and its diameter on the ballistic properties and the failure modes of thin steel targets.

However the mix of the dynamic gas gun technique with specimen heating is not widely spread. There has been few data available for experimental results in which specimens are subjected to impact loading at elevated temperatures. Such analysis has been proposed for the aluminum alloy AL1050. The initial and residual velocity laser sensor is used during experiments to obtain the ballistic curve and ballistic limit. The specimens are heated up to 260 ˚C. The experimental material data obtained have been confronted with available literature data and then extended through FEM analysis.

## 2. Experimental approach

Experimental analysis on aluminum alloy has been carried out using a high pressure gas gun. Perforation tests have been done for a variety of impact velocities from 40 to 120 m/s in order to study the material behavior and to define failure modes. The specimens have been cut from a standard aluminum alloy sheet of 1.0 mm thickness to form 13x13 cm target plates. The conical projectile with an angle of 72° had 13 mm in diameter and its mass was 28 g. The material used for machining the projectile was maraging steel with a heat treatment to reach a yield stress of 2.0 GPa. The specimen and projectile are presented in Fig. 1.



(a) Target (b) Projectile

**Fig. 1** *Dimensions of projectile and target used during perforation tests*

The energy balance is also reported together with the energy absorbed by the aluminum sheet taking into account the ballistic properties. Therefore, the projectile is assumed as rigid during the perforation process [3]. The results in terms of ballistic curve $V_R$-$V_0$ are reported in Fig. 2. The residual velocity of the projectile can be calculated using the following equation proposed by Ipson and Recht [7]:

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

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 k is the ballistic curve shape parameter equal to 1.65.

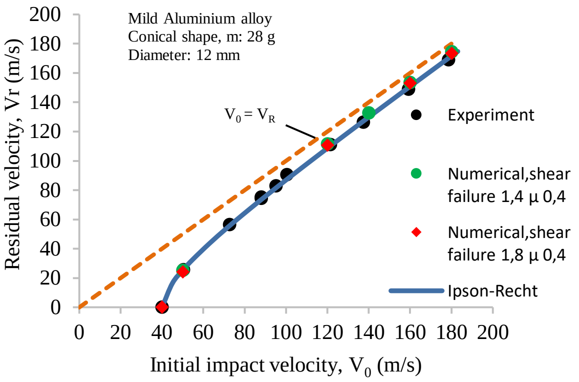


**Fig. 2** *The ballistic curve in experiment and in simulation (room temperature)*

The main aim of the study has been to provide results using an innovative thermal chamber that allows to heat specimens before impact. The range of available temperatures is from room temperature (21 ˚C) up to 270 ˚C. The time duration needed to heat the specimen and stabilize its temperature is 20 minutes. The thermal chamber has been specially calibrated for metals such as aluminum.

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

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

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. 3. Using Eq. 2

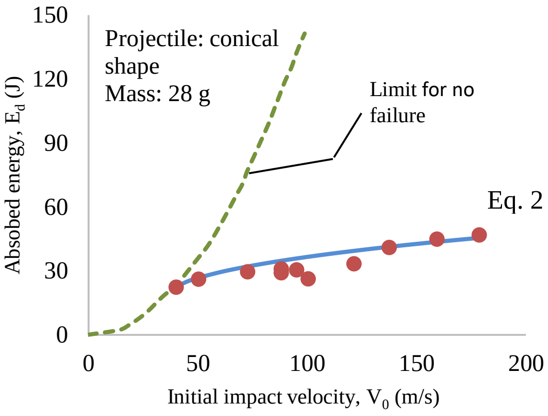


**Fig. 3** *Energy absorbed by the plate during impact test, determination of the failure energy*

## 3. Numerical approach

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

The constitutive relation investigated is described by many 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:

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

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:

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

Numerical models have been built using Abaqus/Explicit. The tests have been conducted for different impact velocities up to 120 m/s. The shell elements type S4R with 8 degrees of freedom and 4 nodes with reduced integration have been used. The element size of 0.5 x 0.5 mm has been adopted. The effectiveness of such elements for this type of analysis was previously proved by Landkof and Goldsmith [8]. 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 and the velocity is defined in the predefined fields with the range of impact velocities from 40 to 120 m/s as conceded in the experiment.

The interior zone of the model allows to initiate the process of crack propagation in a precise way. The projectile behavior has been defined as rigid, because a kinematic coupling constraint (rigid body) has been applied to avoid the deformation of the projectile. The friction coefficient between projectile and specimen is assumed to be equal to 0.2.

## 4. Analysis and conclusions

The mechanical characteristics of the new aluminum alloy have been investigated. The identification of the material parameters have been done using the coupling of the simulation and experimental techniques. The failure modes observed depend on both impact velocity and temperature. Analytical predictions discussed in [7] are fully confirmed for room temperature, whereas more discrepancy in petals number is reported at higher temperatures. The confirmation of experimental data has been obtained in numerical simulations. One example of the deformed shape of the specimen is presented in Fig. 3 where the 4 petals failure is observed. The phenomenological Johnson-Cook constitutive model with the failure criterion has given satisfactory results and can be assumed efficient for this type of analysis.

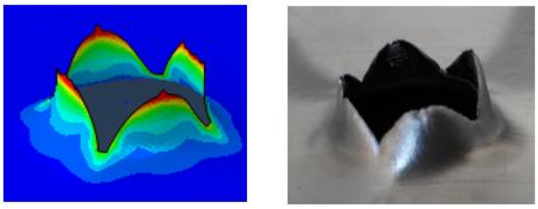


**Fig. 4** *Typical damage phases observed during perforation simulation, thickness=1.0 mm*

Another important observation is the relation between initial and residual velocities of the projectile at different strain rates of loading and at different temperatures. It has been shown that the residual velocity increases with temperature. This is clearer for lower impact velocities. It reflects a softening of the material.

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