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Temperature measurements on ES steel sheets subjected to perforation by hemispherical projectiles

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A R T I C L E I N F O

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This paper is dedicated to **Prof. Janusz Roman Klepaczko** who passed away in August 15, 2008. We pay our tribute to him for his teaching and contribution to dynamic failure of metals. Prof. Klepaczko was involved at the beginning of this investigation.

Keywords:
Perforation
RK model
Infrared thermography
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A B S T R A C T

In this paper is reported a study on the behaviour of **ES** mild steel sheets subjected to perforation by hemispherical projectiles. Experiments have been conducted using a pneumatic cannon within the range of impact velocities $5m/s \leq V_0 \leq 60m/s$. The experimental setup allowed evaluating initial velocity, failure mode and post-mortem deflection of the plates. The tests have been recorded using high speed infrared camera. It made possible to obtain temperature contours of the specimen during impact. Thus, special attention is focussed on the thermal softening of the material which is responsible for instabilities and failure. Assuming adiabatic conditions of deformation, the increase of temperature may be related to the plastic deformation. The critical strain leading to target-failure is evaluated coupling temperature measurements with numerical simulations and with analytical predictions obtained by means of the Rusinek-Klepaczko constitutive relation [Rusinek, A., Klepaczko, J.R. Shear testing of sheet steel at wide range of strain rates and a constitutive relation with strain rate and temperature dependence of the flow stress. Int J Plasticity. 2001; 17, 87–115]. It has been estimated that the process of localization of plastic deformation which leads to target-failure involves local values close to $\bar{\varepsilon}_f^p \approx 1$ for the boundary value problem approached. Subsequently, this failure strain level has been applied to simulate the perforation process and the numerical results obtained show satisfactory agreement with the experiments in terms of ballistic limit, temperature increase and failure mode of the target.

1. Introduction

The study of materials subjected to extreme loading conditions like crash, impact or explosion, has considerable interest for different industrial fields. A relevant amount of publications can be found in the international literature dealing with high strain rate behaviour of metallic materials related with different engineering applications [1–6]. During the last decades, the behaviour of metallic plates when subjected to impact by non-deformable projectiles has gathered the efforts of many researchers [7–18].

Impact processes are strongly dependent on strain hardening $\theta = \partial\sigma/\partial\varepsilon^p$, temperature sensitivity $\upsilon = \partial\sigma/\partial T$ and strain rate sensitivity $m = \partial\sigma/\partial \log(\dot{\varepsilon})$ of the material. Locally, plastic strain values larger than $\bar{\varepsilon}_f^p > 1$ may be reached for some metals under dynamic loading conditions [19–21]. High temperature level inducing thermal softening of the material is usually observed in such processes. It comes from an irreversible thermodynamic process which converts the plastic energy into heat. Adiabatic temperature increase is precursor of plastic instabilities and subsequent failure.

This paper is devoted to the analysis of such complex phenomena which take place during impact processes. An experimental analysis has been conducted on the impact behaviour of **ES** mild steel sheets subjected to perforation by non-deformable hemispherical projectiles. Experiments have been carried out using a pneumatic cannon within the range of impact velocities $5m/s \leq V_0 \leq 60m/s$. The tests were recorded using infrared high speed camera. It allowed obtaining temperature contours during impact. Assuming adiabatic conditions of deformation, temperature increase ΔT may be related to plastic deformation. It makes possible to evaluate the critical failure strain $\bar{\varepsilon}_f^p$ that leads to the collapse of the target. For that task, the temperature measurements are coupled with numerical simulations and with analytical predictions of the material behaviour obtained by means of the constitutive description due to Rusinek and Klepaczko (**RK**) [22].

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2. Material

Mild steel **ES** has considerable relevance since it is widely used in several engineering fields as for example in automotive industry. It has been frequently studied and a significant number of works dealing with the thermo-viscoplastic behaviour of this metal can be found in the literature [17,23–30]. Mild steel **ES** consists of a *ferrite–pearlitic* (**BBC**) structure. The chemical composition of the mild steel **ES** (*% of weight*) is reported in Table 1.

In agreement with experimental evidences reported in [22,26] the behaviour of the steel **ES** can be considered isotropic.

3. Description of the experimental setup

A scheme of the sample used for the perforation tests is shown in Fig. 1. The thickness of the specimen is $h = 1$ mm and its surface is $A_t = 140 \times 140$ mm^2. The active part of the specimen after it is screwed and clamped on the support is $A_f = 100 \times 100$ mm^2. This configuration minimizes the potential distortions in the failure mode of the plates thanks to the boundary conditions.

Several screws symmetrically placed are used to attach the steel sheet to the clamping support, Fig. 1. It allows eliminating potential sliding effect during the tests. The mass of the hemispherical projectile used is $M_p = 0.063$ kg and its dimensions are shown in Fig. 2.

The projectiles were made of *Maragin* steel which exhibits high yield stress $\sigma_y > 1$ GPa, much higher than that corresponding to the **ES** steel under dynamic conditions of deformation, Fig. 15. In addition, the projectiles underwent a heat treatment in order to increase their hardness. A foam sabot was used in order to get the perpendicularity of the impact during the tests. It allowed launching these projectiles whose diameter was considerably smaller than the diameter of the barrel, $\phi_p < \phi_b = 22$ mm.

3.1. The pneumatic cannon

In order to analyze the impact behaviour of the steel sheets within the impact velocity range 5 m/s $\leq V_0 \leq$ 60 m/s, a gas cannon has been used [17,31], Fig. 3-b. This technique allows measuring the initial velocity just before the impact takes place. Such measurement is carried out using 3 sources of light B_i coupled to 3 laser diodes C_i and 3 time counters. When the projectile passes through a source of light, Fig. 3-a, a time counter is trigged. This procedure is repeated 3 times defining two time intervals Δt_{12} and Δt_{23}, Fig. 3-a. Knowing the distance between the 3 sources of light it is possible to measure two instantaneous projectile-velocities V_0^{ij}. Their average $\overline{V}_0$ was used to define the impact velocity values reported along this document.

This experimental technique allows for an accurate definition of the ballistic limit V_{bl} for the boundary value problem examined in this paper.

3.2. Post-mortem measurement of the deflection of the targets

Post-mortem measurement of the targets-deflection was conducted using a 2D-profilometer, Fig. 4-a. It allowed measuring the profiles of the impacted plates with an accuracy of 3 µm ± 1 µm.

Table 1
Chemical composition of the mild steel **ES** (% of weight) [17,30] delivered by Arcelor-Mittal.

Mn	Al	Cr	C	Ni	S	Cu	Si	P	N	Ti
0.203	0.054	0.041	0.03	0.018	0.011	0.009	0.009	0.008	0.0063	0.002

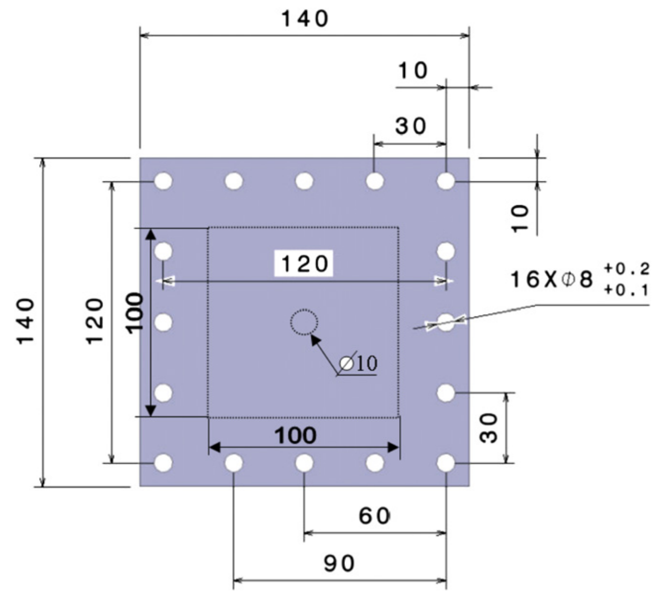

Fig. 1. Specimen used in the experiments.

Since measurements are carried out after impact, the displacement of the steel sheets comes exclusively from plastic deformation, Fig. 4-b. Elastic recovery cannot be taken into consideration.

Additionally, the perforation tests were recorded using a high speed infrared camera.

3.3. Experimental temperature measurements using infrared camera

The infrared camera used for measuring temperature contours features variable "snap shot" integration from 10 µs to 10 ms and frame rates up to 200 FPS (*Frames per Second*) in full frame mode and 6000 FPS in sub-windowing mode. The minimum temperature variation registered by the camera is $\Delta T_{min} = 18\ mK$. The integration time is within the range $1\mu s \leq t_{int} \leq 20\ ms$. Such features allow having high definition and elevated frame-rates. The camera was placed in different positions depending on the impact velocity. In the case of initial velocity below the ballistic limit, the camera was placed on the impact axis, on the back of the sheet steel, (*Position 1*). In the case of impact velocity above ballistic limit, the camera was placed with a small angle $\theta \approx 15°$, in relation to the impact axis in order to guarantee the safety of the device, (*Position 2*) Fig. 5. The distance from the camera to the target remained approximately constant for both camera placements. During the tests it was checked that such camera angle ($\theta \approx 15°$) allowed for a complete view of the rear side of the target during the impact

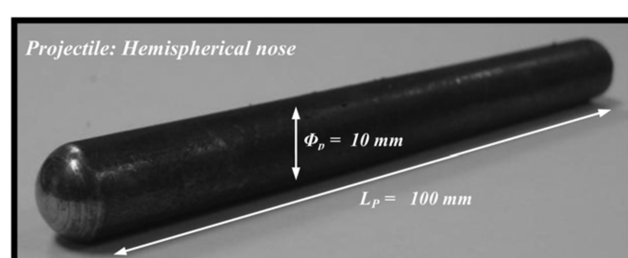

Fig. 2. Projectile used for perforation tests.