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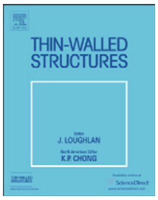

Thermo-viscoplastic behaviour of 2024-T3 aluminium sheets subjected to low velocity perforation at different temperatures

J.A. Rodríguez-Martínez [a],*, A. Rusinek [b], A. Arias [a]

[a] Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain
[b] National Engineering School of Metz (ENIM), Laboratory of Mechanics, Biomechanics, Polymers and Structures (LaBPS), 1 route d'Ars Laquenexy, 57078 Metz Cedex 3, France

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ABSTRACT

This paper deals with the mechanical behaviour of the aluminium alloy **2024-T3**. This alloy has particular relevance since it is widely used in the aeronautical industry for building aircraft structures. The deformation behaviour of this material has been characterised in tension under wide ranges of strain rate and temperature. Among the aluminium alloys, the **AA 2024-T3** highlights due to its high flow stress and strain hardening. Moreover, the material temperature sensitivity has been found dependent on plastic strain. The **M**odified **R**usinek–**K**lepaczko constitutive description [Rusinek A, Rodríguez-Martínez JA, Arias A. A thermo-viscoplastic constitutive model for FCC metals with application to OFHC copper. Int. J. Mech. Sci. 52 (2010) 120–135], which takes into account such dependence of the temperature sensitivity on plastic strain, has been applied for modelling the thermo-viscoplastic response of the material. Satisfactory agreement between experiments and analytical predictions provided by the **M**odified **R**usinek–**K**lepaczko model has been found. In order to study the material behaviour under impact loading, low velocity perforation tests on **AA 2024-T3** sheets have been performed at different initial temperatures using a drop weight tower. Plastic instabilities formation and progression are identified as the cause behind the target collapse for all the impact tests conducted. The results from these perforation tests are compared with those reported in [Rodríguez-Martínez JA, Pesci R, Rusinek A, Arias A, Zaera R, Pedroche DA. Thermo-mechanical behaviour of TRIP 1000 steel sheets subjected to low velocity perforation by conical projectiles at different temperatures. Int. J. Solids Struct. 47 (2010) 1268–1284.] for **TRIP 1000** steel sheets. The comparison reveals that the amount of specific energy absorbed by the aluminium targets is much lower than that corresponding to the steel targets. The role played by inertia on delaying plastic instabilities formation is determined as potential responsible for such behaviour.

1. Introduction

Structural impact has become increasingly relevant for numerous engineering fields like aeronautical, naval or automotive industry. Among the materials traditionally investigated for building protection structures responsible for energy absorption in high loading rate events, the light-weight alloys have particular interest. A considerably amount of scientific works has been published over the last decades dealing with the mechanical response of magnesium, titanium and aluminium alloys subjected to impact loading [1–7].

Those investigations answer to the requirements of the previously mentioned industrial sectors of replacing traditional steel alloys by such metallic materials with improved strength-to-weight ratio [5–8]. In particular, aluminium alloys are being widely introduced for building automobile and aircraft structures. This trend is enhanced by the key factor which represents fuel economy in design stages.

Among the impact events on aluminium structures, perforation processes have gathered the efforts of many researchers [9–12]. The works due to Borvik and co-workers [13–16] and Gupta and co-workers [17–21] are distinguished by their relevance in this field. In those works the response of aluminium plates subjected to perforation by non-deformable projectiles is comprehensively approached. The attention was mainly focused on two different aspects: providing an accurate description of the thermo-viscoplastic behaviour of the material and determination of the deformation mechanisms involved in the process of energy absorption during perforation.

In the present investigation is made common cause with those purposes and the attention is focused on the mechanical behaviour of the aluminium alloy (**AA**) **2024-T3**. This metal is widely applied in the aeronautical industry for construction of mechanical elements with elevated structural responsibility. The thermo-mechanical behaviour of the material is characterised in tension under wide ranges of strain rate and temperature.

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* Corresponding author. Tel.: +34 91 624 8809; fax: +34 91 624 9430.
E-mail address: jarmarti@ing.uc3m.es (J.A. Rodríguez-Martínez).

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Its thermo-viscoplastic response under loading has been modelled by means of the **M**odified **R**usinek–**K**lepaczko (**MRK**) constitutive description [22]. Such physical-based model allows gathering the influence that plastic strain has on the rate sensitivity of this material. Satisfactory agreement between experiments and analytical predictions of the **MRK** model is found. This physical-based modelling of the material behaviour constitutes an improvement with respect to the purely phenomenological descriptions commonly applied in the literature for prediction of aluminium alloys response under dynamic solicitations [16,20–21,23].

Moreover, the impact/perforation behaviour of this alloy is examined. Low velocity perforation tests on **AA 2024-T3** sheets are conducted at different initial temperatures using a drop weight tower. The process of strain localisation and subsequent plastic instabilities progression are determined responsible for the target collapse in all the impact tests conducted. The results obtained from these perforation tests are compared with those reported by Rodríguez-Martínez et al. [24] for **TRIP 1000** steel sheets. The comparison reveals that the amount of specific energy absorbed by the aluminium targets is much lower than that corresponding to the steel targets. The role played by inertia on delaying plastic instabilities formation is determined as potential responsible for such behaviour. The research conducted shows the necessity to assess the suitability of certain light-weight alloys for absorbing energy in dynamic events involving instabilities and failure.

2. Experimental characterisation of the thermo-viscoplastic behaviour of the AA 2024-T3

The **AA 2024-T3** is an aluminium alloy, with **Cu** and **Mg** as the main alloying elements. The chemical composition of the material (*% of weight*) is reported in Table 1.

It shows good machinability and surface finish capabilities. It is a high strength aluminium alloy of adequate workability. It is widely used in aircraft structures where stiffness, fatigue performance and good strength are required. Other applications comprise hydraulic valve bodies, missile parts, munitions, nuts or pistons.

The thermo-viscoplastic behaviour of the material has been characterised in tension under wide ranges of strain rate $0.001\,s^{-1} \leq \dot{\varepsilon} \leq 200 s^{-1}$ and temperature $223\,\text{K} \leq T_0 \leq 373\,\text{K}$. The geometry and dimensions of the tensile specimens used in the characterisation are depicted in Fig. 1.

In Fig. 2, the material flow stress evolution as a function of strain at low strain rates and room temperature is shown. Among the aluminium alloys, the **AA 2024-T3** highlights due to its high flow stress and hardening rate which enhances its capability for absorbing energy in loading processes, Fig. 2.

Table 1
Chemical composition of the **AA 2024-T3** (% of weight).

Mn	Si	Cr	Ti	Fe	Mg	Zn	Cu
0.6	0.5	0.1	0.15	0.5	1.5	0.25	4.3

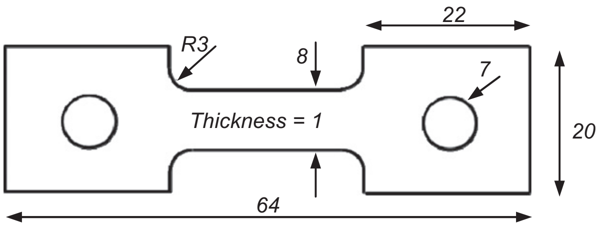

Fig. 1. Geometry and dimensions of the tensile specimens used for the mechanical characterisation of the material at low and high strain rates (mm).

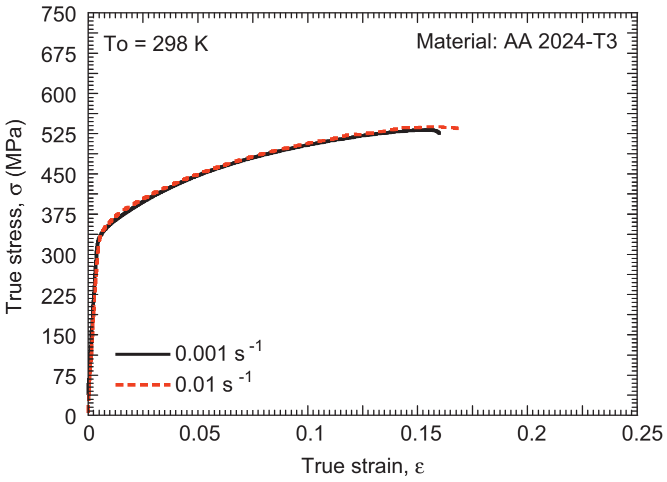

Fig. 2. Flow stress evolution versus strain for different low strain rates at room temperature.

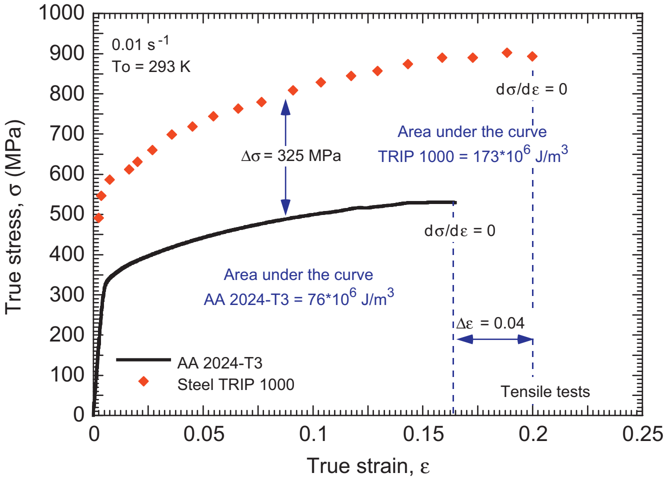

Fig. 3. Flow stress evolution as a function of strain at low strain rate and room temperature. Comparison between **AA 2024-T3** and steel **TRIP 1000** [25].

Those characteristics are clearly noticed when the mechanical behaviour of the **AA 2024-T3** is compared, for example, with that corresponding to a **H**igh **S**trength **S**teel like **TRIP 1000**, Fig. 3. The comparison with the steel **TRIP 1000** is justified since, later on, perforation tests conducted on both materials will be compared. The tensile specimens used for characterisation of the mechanical behaviour of the **TRIP 1000** [25] also answer to the geometry and dimensions illustrated in Fig. 1.

Bearing in mind that the density of aluminium is lower than that of steel $\rho_{\text{AA2024-T3}}/\rho_{\text{TRIP 1000}} \approx 0.35$ (where $\rho_{\text{AA2024-T3}} = 2700\,\text{kg/m}^3$ and $\rho_{\text{TRIP1000}} = 7800\,\text{kg/m}^3$); it has been observed that, comparatively, the **AA 2024-T3** displays remarkable ratios of flow stress $\sigma|_{\dot{\varepsilon},T}^{\text{AA 2024-T3}}/\sigma|_{\dot{\varepsilon},T}^{\text{TRIP 1000}} \approx 0.65$, hardening rate $\partial\sigma/\partial\varepsilon^p|_{\dot{\varepsilon},T}^{\text{AA 2024-T3}}/\partial\sigma/\partial\varepsilon^p|_{\dot{\varepsilon},T}^{\text{TRIP 1000}} \approx 1$ and ductility $\varepsilon_{\text{failure}}|_{\dot{\varepsilon},T}^{\text{AA 2024-T3}}/\varepsilon_{\text{failure}}|_{\dot{\varepsilon},T}^{\text{TRIP 1000}} \approx 0.8$, Fig. 3.

Moreover, let us calculate the energy per unit volume absorbed by both metals in the tests reported in Fig. 3. This corresponds to