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Thermo-mechanical behaviour of TRIP 1000 steel sheets subjected to low velocity perforation by conical projectiles at different temperatures

J.A. Rodríguez-Martínez [a,*], R. Pesci [b], A. Rusinek [c], A. Arias [a], R. Zaera [a], D.A. Pedroche [a]

[a] *Department of Continuum Mechanics and Structural Analysis, University Carlos III of Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain*
[b] *ENSAM, Laboratory of Physics and Mechanics of Materials (LPMM), FRE CNRS 3236, 4 Rue Augustin Fresnel, 57078 Metz Cedex 3, France*
[c] *National Engineering School of Metz (ENIM), Laboratory of Mechanics, Biomechanics, Polymers and Structures (LaBPS), Ile du Saulcy, 57000 Metz, France*

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Dedicated to Professor Wojciech Nowacki, director of IPPT, who passed away on August 14, 2009.

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ABSTRACT

This paper presents and analyzes the behaviour of TRIP 1000 steel sheets subjected to low velocity perforation by conical projectiles. The relevance of this material resides in the potential transformation of retained *austenite* to *martensite* during impact loading. This process leads to an increase in strength and ductility of the material. However, this transformation takes place only under certain loading conditions strongly dependent on the initial temperature and deformation rate. In order to study the material behaviour under impact loading, perforation tests have been performed using a drop weight tower. Experiments were carried out at two different initial temperatures $T_0 = 213$ K and $T_0 = 288$ K, and within the range of impact velocities 2.5 m/s $\leqslant V_0 \leqslant$ 4.5 m/s. The experimental setup enabled the measuring of impact velocity, residual velocity, load-time history and failure mode. In addition, dry and lubricated contacts between the striker and the plate have been investigated. Finally, by using X-ray diffraction it has been shown that no *martensitic* transformation takes place during the perforation process. The causes involving the none-appearance of *martensite* are examined.

1. Introduction

In the last decades, manufacturers have tried to minimize the production time and costs, while improving the properties and the quality of the products. This is also the case for important economic sectors like the automobile, naval or civil industries, which have invested substantial efforts in developing new generations of steels for light-weight structures capable of bearing strong mechanical and thermo-mechanical loading. In order to fulfil these objectives, new alloys with high strength, ductility and toughness have been developed. Among them, the high strength TRIP steels (Transformation Induced Plasticity) have become of great relevance.

These steels exhibit the transformation of *austenite* to *martensite* under determined loading conditions. This transformation phenomenon is desirable during impact loading since it increases the strength and ductility of the material retarding plastic localization as described by Curtze et al. (2009), Da Rocha and Silva de Oliveira (2009), Delannay et al. (2008), Fischer et al. (2000) and Jiménez et al. (2009).

According to Delannay et al. (2008), transformation of *austenite* into *martensite* can be triggered either by quenching or by loading the sample. Two effects are responsible for the deformation process taking place in TRIP steels during and after the phase transformation as shown by Delannay et al. (2008), Fischer et al. (2000) and Leblond et al. (1989):

- The "Magee effect" described by Magee (1966) is related to orientation processes due to transformation of preferred variants.
- The "Greenwood–Johnson effect" described by Greenwood and Johnson (1965) is related to the displacive character of the *austenite-martensite* transformation as discussed in Leblond et al. (1989). It corresponds to the plastic strain induced in the parent phase because of the volume difference between two coexisting phases.

The influence of plastic deformation, loading rate and initial temperature on the transformation kinetics of TRIP and dual phase steels has been analyzed by many researchers, for example Al-Abbasi and Nemes (2003), Bouaziz and Guelton (2001), Bouaziz et al. (2008), Curtze et al. (2009), Huh et al. (2008), Iwamoto et al. (1998), Iwamoto and Tsuta (2000), Jiménez et al. (2009), Larour et al. (2006), Meftah et al. (2007), Papatriantafillou et al. (2006), Rodríguez-Martínez et al. (2009) and Taleb and Petit (2006).

From these previous works several conclusions can be drawn:

- Plastic deformation triggers the *martensitic* transformation. It provides the driving force, (*corresponding to the difference in the free energy between austenite and martensite*) necessary to initiate and achieve the transformation.

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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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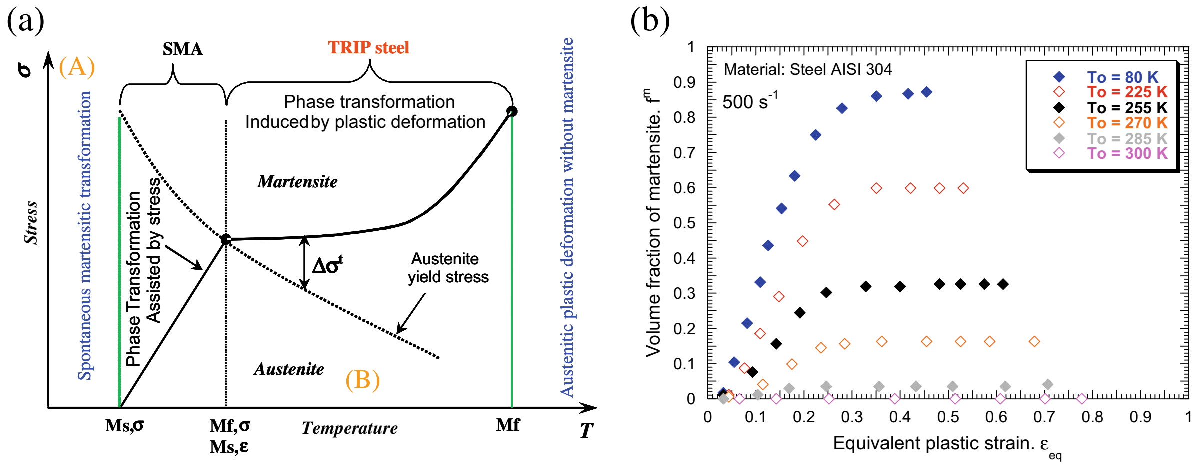

Fig. 1. (a) Schematic representation of the temperature effect on the martensitic transformation in TRIP steels. (b) Transformed volume fraction of martensite as a function of plastic strain in AISI 304 stainless steel, strain rate 500 s^{-1} (Tomita and Iwamoto, 1995).

- *Martensitic* transformation is strongly dependent on the initial temperature as illustrated in the schematic drawing of Fig. 1a. The driving force required to induce the transformation varies with the temperature. For temperatures under a certain level M_s, the transformation may be reached in absence of plastic deformation. For temperatures above a critical value M_f, *martensite* will not be formed, no matter how much the *austenite* is deformed as reported by Lebedev and Kosarchuk (2000).
- Due to the relation existing between deformation and temperature in the material behaviour, the strain rate also plays a crucial role in the phase transformation process. For high strain rates, the *martensitic* transformation could not exist, Fig. 1b. Thermal softening of the material due to adiabatic heating under dynamic loading prevents the phase transformation.

Moreover, it is necessary to distinguish between two different types of TRIP steels:

- The high-alloy TRIP steels (H-TRIP) such as AISI 304, 301 or the high manganese steels. These *austenitic* steels contain large amounts of alloying elements such as Cr, Ni and/or Mn which stabilize the *austenite* as outlined by Fischer et al. (2000) and Liu et al. (2008).
- The low-alloy TRIP steels (L-TRIP) such as TRIP 600, 800, 1000 present a microstructure consisting of *ferrite*, *bainite* and retained *austenite* at room temperature. Generally, they contain small amounts of *austenite* stabilisers, which promotes the phase transformation as reported in Fischer et al. (2000) and Liu et al. (2008), Fig. 2.

Due to the different microstructures the transformation mechanisms are slightly different depending on the type of TRIP steel considered as described by Delannay et al. (2008) and Fischer et al. (2000).

In the present work, the attention will be focussed on the second type of TRIP steels previously mentioned. Generally, in L-TRIP steels the retained *austenite* represents less than 20% of the total volume and only a fraction of *austenite* may transform during loading. These multiphase steels can be treated, in some measure, as composite materials, where the retained *austenite* acts as a second phase embedded in a *ferrite–bainite* matrix. The transformation is basically controlled by the “Greenwood–Johnson effect” as reported by Delannay et al. (2008). As a consequence of the *martensitic* transformation, strong local plasticity enhances strain hardening and global strain of the material. The L-TRIP steel grades have major technological importance in comparison with the

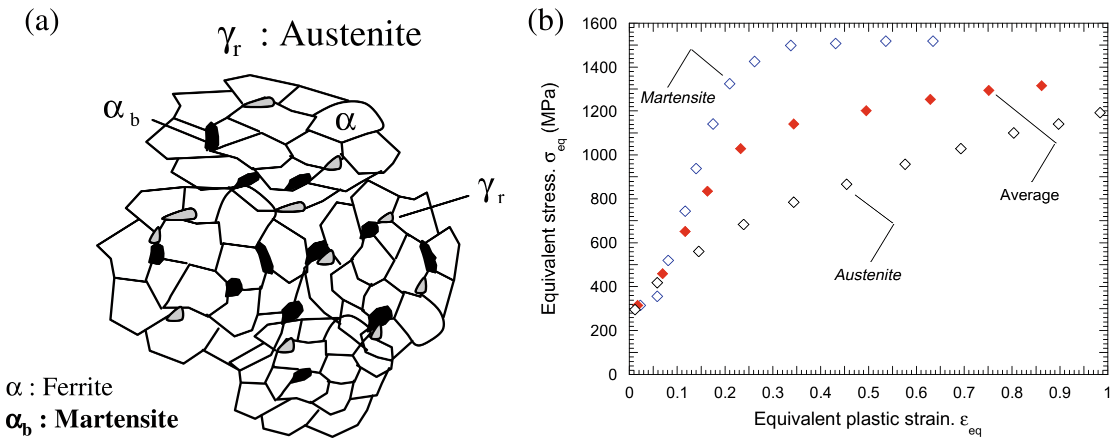

Fig. 2. (a) Sketch of the microstructure of a L-TRIP steel. (b) Stress–strain diagram showing the progressions of stress–strain curves of austenite, martensite and of an austenitic-martensitic microstructure (Iwamoto et al., 1998).