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Experiments on heat generated during plastic deformation and stored energy for TRIP steels

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ABSTRACT

The goal of this study is to analyze the effect of heat generation during plastic deformation in new sheet steel with high strength on the mechanical behavior during relaxation test $\sigma(t)|_{\varepsilon_p}$ and during tension at constant strain rate. In the first part an estimation of the fraction β of plastic work converted into heat has been analyzed with and without phase transformation [Rosakis P, Rosakis AJ, Ravichandran G, Hodowany J. On the partition of plastic work into heat and stored energy in metals: Part II. Theory, Internal SM Report No. 98-8. California Institute of Technology, June 1998]. It is shown that β increases with plastic deformation. The latent heat due to phase transformation plays an important role. In order to analyze those effects, a fast hydraulic machine has been used combined with an infrared technique allowing measurement of temperature increase with plastic deformation. This experiment has been performed in adiabatic conditions, $\dot{\varepsilon} \geqslant 10\ \mathrm{s}^{-1}$. The value found for β vary within the limits: $0.82 \leqslant \beta \leqslant 1$. In the second part the temperature effect due to plastic deformation has been analyzed via relaxation test. Due to high stress level and high ductility, relatively high temperature increase ΔT was found in fast and quasi-static loading. The temperature effect is relatively important for the creep observed during testing. Such behavior is completely different in comparison to mild steel where the temperature increase is much lower [Rusinek A, Zaera R, Klepaczko JR, Cheriguene R. Analysis of inertia and scale effects on dynamic neck formation during tension of sheet steel. Acta Mater 2005;53:5387–400]. In the third part, experimental results are reported concerning plastic instability, notably Lüder's band propagation. An estimation of temperature increase in the band has been performed.

1. Introduction

Recently, new kinds of sheet steels are developed for automotive applications, for example DP, TRIP, Duplex, HLE and others [3]. The main advantages of these materials are combination of high ductility with high stress level; the ultimate stress $\sigma_{\max} \approx 1$ GPa, and maximum deformation in tension $\varepsilon_{\max} \approx 0.3$. Thus, the plastic work W_p converted into heat Q_p during the process of deformation is very important. The ratio of plastic work converted into heat is defined by the quantity β

$$\beta = \frac{\dot{Q}_p}{\dot{W}_p} \tag{1}$$

This quantity defines in fact the fraction of stored energy ζ of the cold work due to the creation, rearrangement of crystal defects and formation of dislocation structures. The fraction of stored energy is defined by

$$\zeta = 1 - \beta \tag{2}$$

A method proposed by Oliferuk et al. [4] allows to observe the dependency of ζ, or $\beta = 1 - \zeta$, on strain at different loading directions in tension test of a sheet. A small anisotropic effect on the value of β was found but an important effect is the level of pre-strain.

Moreover, this coefficient is generally assumed as a constant independent of plastic deformation and strain rate and its value is commonly accepted as $\beta = 0.9$. However, the coefficient β may be estimated more precisely with application of infrared technique combined with a high-speed test. In such test arrangement the adiabatic conditions can be reached, when the heat conduction is substantially reduced.

Several authors studied the evolution of β as a function of plastic deformation [5]. Some values for different steels taken from variety of sources are given in Table 1.

A dependency β on the apparition time t_c of plastic instabilities like adiabatic shear bands (ASB) was also reported in [11]. In fact, t_c is directly related to the competition between T and $\dot{\varepsilon}_p$ in evolution of β during plastic deformation. Where T and $\dot{\varepsilon}_p$ are, respectively, the absolute temperature and plastic strain rate. In the present case, an experimental study is reported on the effect of plastic work converted into heat during plastic deformation of high

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Table 1
Evaluation of the Taylor–Quinney coefficient β for different steels and iron

Steel	Test	Strain rate ($1\,s^{-1}$)	β	$\bar{\beta}$	Reference
4340	C	3000	0.4–0.9	0.75	[6]
Mild	T	0.003	0.87–0.93	0.90	[7]
224	C	4	0.95	0.95	[8]
1018	C	3000	0.8	0.8	[9]
Carb. steel	–[a]	–[a]	1	1	[1]
AISI 304L	–[a]	–[a]	0.9	0.9	[4]
Iron	–[a]	–[a]	0.95	0.95	[11]

C, compression; T, torsion.
[a] Data unknown.

strength steel TRIP 800. The chemical composition of TRIP 800 is given in Table 2.

The originality of this material in comparison with mild steels is presence of phase transformation of austenite into martensite during plastic deformation. The physics is similar as in the shape memory alloys (SMA) but in this case with a reduced initial volume of austenite (Table 2 and Fig. 1a and b). Generally, the plastic deformation is accompanied by generation of a latent heat due to the phenomenon of phase transformation [12,13]. Such effect is very important in SMA since 100% of the austenite is transformed into martensite. However, for TRIP steel this proportion is reduced and decreases when the temperature increases.

2. Application to new generation of sheet steel with high ultimate strength, TRIP steel

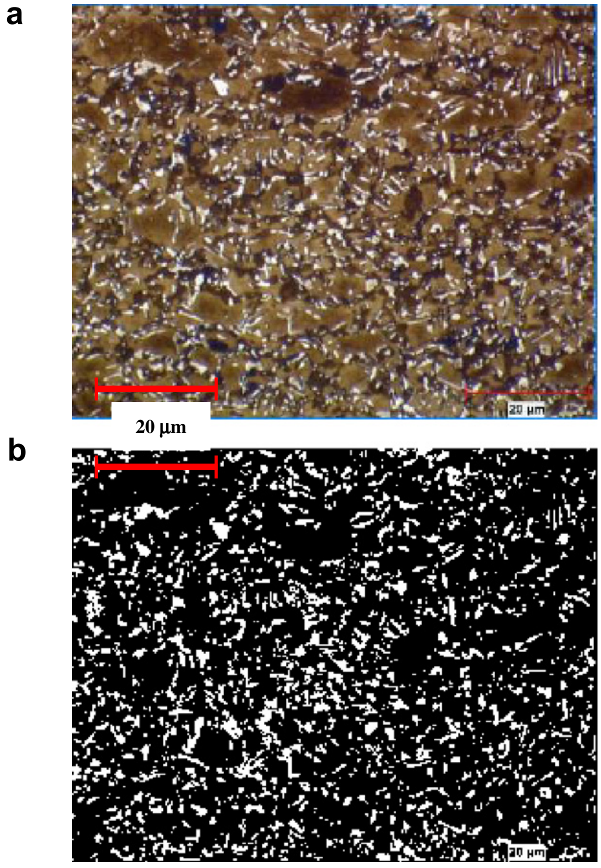
In the first part of this study a review is performed on analysis of temperature and strain rate effects in behavior of the TRIP steel [14,15]. Some previous results are presented in this paper just to synthesize several different effects. In the following figure, the temperature sensitivity of the flow stress is demonstrated (Fig. 1). In this figure, one can observe an important effect of the initial temperature which is non-proportional to the temperature changes during plastic deformation [14]. Such stress evolution is directly related to the phase transformation as discussed in [14,15]. For this material two temperatures can be defined. The lower temperature, where the phase transformation appears instantaneously without plastic deformation, $T_{min} = 213$ K, and the upper limit where the residual austenite is stable. In the last case, for temperature higher than $T_{max} = 373$ K the process of plastic deformation occurs without phase transformation. Due to precise experimental technique, a complete investigation has also been performed concerning the strain rate sensitivity (Fig. 2). In that figure, a reduction of strain rate sensitivity is observed at room temperature. The transition strain rate characterizing the athermal and thermal activation ranges may be defined as $\dot{\varepsilon}_{trans.} \geqslant 10\ s^{-1}$. The transition is defined by a substantial stress increase defined by the slope of the $\sigma - \log(\dot{\varepsilon})$ function, which is proportional to the apparent volume of thermal activation V^* defined by

$$V^* = kT \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma^*}\bigg|_{T,\varepsilon_p} \tag{3}$$

where k is the Boltzmann constant and σ^* is the effective stress, $(\sigma = \sigma_{ath} + \sigma^*)$, $\sigma^* \approx 0$ in quasi-static loading. As shown in Fig. 2, it is clear that the temperature decrease induces a decrease of the strain rate transition. For example for $T = 213$ K the value is $\dot{\varepsilon}_{trans.} \approx 0.3\ s^{-1}$.

Table 2
Chemical composition of TRIP 800 steel produced by Arcelor–Mittal group – components defined in wt%

Name	C	Mn	Si	Retained austenite
TRIP 800	0.25	2	2	~18



Ferrite (Black) - Residual austenite and bainite (white)

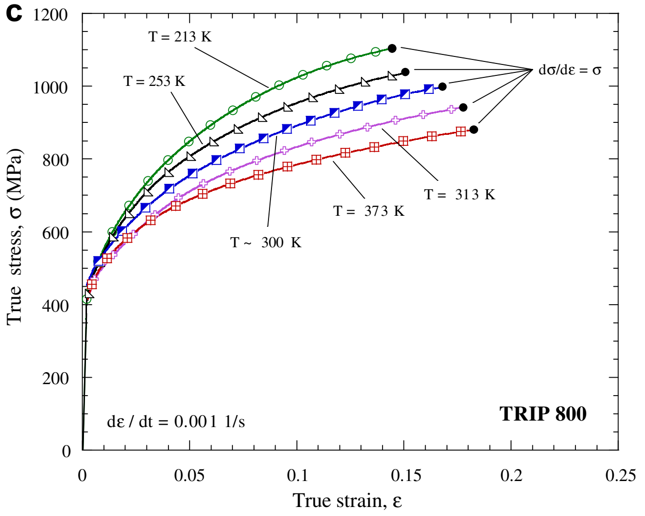


Fig. 1. (a) Microstructure of TRIP 800 steel [33], (b) phase distribution and (c) effect of the initial temperature on plastic behavior of TRIP 800 steel during quasi-static tension test.

With such experimental data, it is possible to find the evolution of the Taylor–Quinney coefficient β in adiabatic conditions and to analyze the effect of phase transformation. In the following part, several estimation methods are proposed using several approaches like in [1] and [16]. In the first method the constitutive relation $(\sigma, \varepsilon, \dot{\varepsilon}, T)$ is applied, and in the second only the hardening rate is