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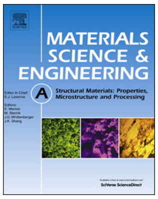

Temperature and strain rate effects on the mechanical behavior of dual phase steel

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ABSTRACT

The effect of temperature and strain rate on the mechanical behavior of a commercial dual phase steel (DP 800) has been investigated experimentally by uniaxial tensile tests in this study, covering temperatures (−60 °C to 100 °C) and strain rates (1×10^{-4} to $1\times10^{2}\ \mathrm{s}^{-1}$) encompassing conditions experienced in automotive crash situations. Yield and ultimate tensile strength, ductility, temperature effects and strain rate sensitivity have been determined and discussed. It was found that the Voce equation [$\sigma=\sigma_s-(\sigma_s-\sigma_0)\exp(-\varepsilon\theta_0/\sigma_s))$] can be satisfactorily applied to describe the tensile flow curves by means of a modified Kocks–Mecking model. In this model the parameter θ_0 is fixed, whereas both σ_0 and σ_s consist of athermal and thermal stress components. The athermal component is only weakly dependent on temperature through the elastic shear modulus μ. The thermal stress component is governed by temperature and strain rate. Statistical analysis based on the experimental data has allowed all parameters in the Voce equation to be quantified.

1. Introduction

In order to reduce fuel consumption and emissions, it is necessary to design low weight car bodies in the automotive industry. Materials able to lower the body weight are thus in great demand. One way of weight saving is to use low density materials, such as Al alloys. Using high strength formable steels is another way to meet the weight requirement. One example in this family is dual phase (DP) steel sheets which have a microstructure consisting of hard martensite (M) islands embedded in a soft matrix of ferrite (F). Such a microstructure is created by intercritical annealing or by controlled cooling after hot rolling. As martensite is formed from transformation of austenite (A) upon cooling, this steel often contains some retained austenite.

The mechanical properties of DP steel have been studied by many investigators, e.g. Refs. [1–5]. The microstructure provides an excellent combination of strength and ductility, which ensures both good formability and a high final strength after press forming. This kind of microstructure possesses smooth stress strain curves and exhibits continuous yielding behavior with high work hardening rate and strain hardening ratio as well as high uniform and total elongation. It has been observed that the commercial grades DP 600 and DP 800 show a positive strain rate sensitivity in the strain rate range 0.003–1500 s^{-1} [5] and a reduction in strength at elevated temperatures. Static [6,7] and dynamic [2] strain aging characteristics have also been reported.

In crash situations, the mechanical response of the car body at actual local temperatures and strain rates determines the energy absorption and is thus of great importance for the structural integrity. In addition, structural analyses and safety assessments require constitutive relations between strain and flow stress which again contain temperature and strain rate as important parameters. In this study, tensile tests have been performed on the commercial dual phase steel DP 800 covering applicable temperatures and strain rates experienced in automotive crash situations. The paper first provides experimental data followed by an interpretative discussion. Subsequently, the Voce stress–strain equation is applied to fit the experimental data by considering the Kocks–Mecking (KM) model [8] with some modifications. The model parameters are expressed analytically and can thus be implemented in software for stress analysis to accurately model the material behavior in crash situations.

2. Theoretical background

2.1. Voce equation and Kocks–Mecking model

The Voce equation [11] can be used to express the tensile flow and work hardening in the linear steady state. It is consistent with the Kocks–Mecking (KM) model which takes into account storage and dynamic annihilation of dislocations [8–11] based on thermally

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activated processes. It can be written in the form:

$$\sigma=\sigma_s-(\sigma_s-\sigma_0)\exp(-\varepsilon/\varepsilon_0), \tag{1}$$

where σ_s is an saturation stress where the work hardening rate becomes zero, corresponding to equilibrium between dislocation storage and dynamic recovery. The density and arrangement of the dislocations are constant in this case, corresponding to a saturated dislocation substructure. It should be noticed that it is impossible to reach such a situation in a tensile test because of necking of the bar. σ_0 is the extrapolated initial stress associated with the beginning of plastic deformation and ε_0 is a characteristic strain, determined by the recovery rate corresponding to annihilation of dislocations. ε_0 is related to σ_s via the initial strain hardening rate θ_0 in the stage II deformation via Eq. (2):

$$\varepsilon_0=\sigma_s/\theta_0 \tag{2}$$

It is generally accepted that θ_0 is independent of temperature and strain rate. By substituting ε_0 with θ_0, Eq. (1) can be re-written as Eq. (3).

$$\sigma=\sigma_s-(\sigma_s-\sigma_0)\exp(-\varepsilon\theta_0/\sigma_s) \tag{3}$$

It has been shown experimentally that the logarithm of the saturation stress σ_s varies approximately linearly with temperature T and logarithmically with strain rate ($\dot{\varepsilon}$) in fcc metals [10,11]. An empirical expression can then be written as

$$\ln\frac{\sigma_s}{\sigma_{s0}}=-\frac{kT}{A\mu b^3}\ln\left(\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}\right), \tag{4}$$

where k is Boltzmann constant, μ the temperature dependent shear modulus, b Burgers vector, $\dot{\varepsilon}_0$ a reference strain rate and A, σ_{s0} constants.

2.2. Athermal and thermal stress components of flow stress

It is well known that the critical shear stress τ_s for plastic deformation can be separated into two components, namely thermal and athermal stress parts. The proportionality between shear and normal stresses allows σ to be divided similarly, as indicated by Eq. (5).

$$\sigma=\sigma_a+\sigma_t \tag{5}$$

The athermal stress component σ_a depends on large obstacles (e.g. particles or dislocation bundles) creating long-range stress fields, while the thermal component originates from smaller obstacles, only locally disturbing the stress field. The former one is only weakly dependent on temperature through the elastic shear modulus μ and is strongly dependent on microstructure. The athermal stress is sometimes considered as a material constant, but a strain dependence does exist, as reported by Refs. [12–14].

The thermal component σ_t is a function of plastic strain rate and temperature and can be reduced by thermal activation. Thermal activation analysis [10] gives:

$$\left(\frac{\sigma_t}{\hat{\sigma}_t}\right)^p=1-\left(\frac{kT\ln\frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}}{g_0\mu b^3}\right)^{1/q}. \tag{6}$$

here, $\hat{\sigma}_t$ is the thermal mechanical threshold stress at 0 K, g_0 a normalized activation energy, k Boltzmann constant, μ temperature dependent shear modulus and b Burgers vector. p and q are constants that characterize the shape of the obstacle profile with $0\le p\le 1$, $1\le q\le 2$.

3. Experimental

3.1. Material

A commercial dual phase steel (called DP 800) supplied by SSAB (Swedish Steel AB)in the form of rolled sheet with a thickness of 2 mm was investigated in this study. The chemical composition and mechanical properties at room temperature of the alloy are listed in Tables 1 and 2, where the tensile data refer to the longitudinal direction. The microstructure consists of a mixture of ferrite grains and martensite islands along the rolling direction (Fig. 1). The etchant used here is 2 g ammonium persulfate, 2 ml HF, 50 ml acetic acid and 150 ml H_2O. The volume fractions of ferrite and martensite are roughly 2/3 and 1/3 respectively, often with contiguity of the ferrite grains, although the martensite islands are partly interconnected. A small amount of retained austenite is also observed. Despite the elongated hard martensite islands, the mechanical behavior is rather similar in the two main directions with somewhat lower tensile strength and higher elongation in the longitudinal direction. In the transverse direction, it was found that the tensile strength is about 3% larger and uniform elongation some 10% smaller at room temperature with strain rates $1\times10^{-4}\,s^{-1}$. In a microstructure like this with inclusions having a hardness typically 3–4 times larger than that of the matrix, the soft ferrite takes up the majority of the plastic straining, while the role of the mainly elastically loaded martensite islands is to enhance the global hardening and thus formability.

Table 1
Chemical composition of the steel studied [wt%].

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.11	0.2	1.4	0.0091	0.0038	0.03	0.05	0.010	0.01
V	**Al**	**Sn**	**Ti**	**As**	**B**	**Nb**	**Co**	**N**
0.0063	0.0424	0.0029	0.0024	0.0016	0.0003	0.014	0.015	0.0086

Table 2
Basic properties at room temperature of the steel studied.

$R_{p0.2}$ (MPa)	R_m (MPa)	Hardness HV10	Total elongation A_{10}
540	830	247 ± 7	≈ 0.14

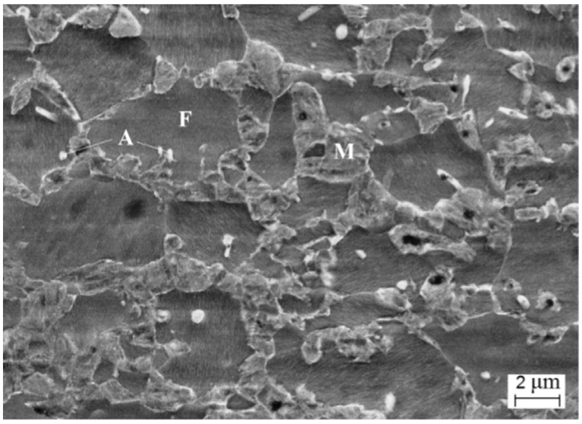

Fig. 1. Microstructure of the studied DP steel. Micrograph parallel to rolling plane. Rolling direction horizontal.