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Constitutive relationships for 22MnB5 boron steel deformed isothermally at high temperatures

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Abstract

The strain, strain rate and temperature dependency of a boron steel, which was isothermally deformed under uniaxial compression tests, has been investigated at temperatures between 600 and 900°C, and at strain rates of 0.1, 1.0 and 10.0 s^{-1}. Two constitutive models were used to correlate the plastic behavior: the Voce constitutive relation in combination with the kinetic model proposed by Kocks and the phenomenological model proposed by Molinari–Ravichandran. The Kocks model has been introduced in the Voce formulation to describe the temperature and the strain rate dependency of the saturation stress and of the yield stress. The Molinari–Ravichandran model is based on a single internal variable that can be viewed as being related to a characteristic length scale of the microstructure that develops during deformation. It has been shown that the plastic behavior of the boron steel can be well described using these two models.

Keywords: High temperature deformation; Constitutive modeling; Dynamic plasticity

1. Introduction

The application of ultra high strength steels in automotive industries has increased, due to the need for higher passive safety and weight reduction. Hot stamping is an innovative technique to produce ultra high strength steel components like side impact and bumper beams by using boron steels. Deformation in this process is carried out at high temperature, in the austenitic region where the material has FCC structure. The experimental characterization of the material response in austenitic state at different loading conditions, i.e. various strain rates and temperatures are necessary but very expensive and time consuming. Constitutive modeling is particularly helpful for the numerical simulation of industrial applications. Recently, hot working modeling of steels in the austenitic state has been reviewed [1–5]. Generally, the flow stress of a material is described by the following relationship [6]:

$$\sigma = \sigma(\varepsilon, \dot{\varepsilon}, T) \tag{1}$$

The high temperature behavior of a boron steel has been investigated in the temperature range 600–900 °C. The strain rate, temperature and adiabatic softening effects on the flow curves were carefully analyzed using two constitutive models: the Voce–Kocks combined model [7,8] and the Molinari–Ravichandran model [9]. In its original version, the Voce formulation refers to three parameters (the initial yield stress, the saturation stress and the relaxation strain) which are considered rate and temperature insensitive. In this study, the kinetic model proposed by Kocks [8] is introduced in the Voce formulation in order to describe the strain rate and temperature dependency of the initial and saturation stresses. A power law is also proposed to describe the strain rate and temperature dependence of the relaxation strain.

2. Experiments

The material analyzed in this study is hot rolled plate 22MnB5 steel. The chemical composition is listed in Table 1. The Continuous Cooling Transformation (CCT) diagram, Fig. 1, has been determined by dilatometry tests, metallographic investigations and hardness measurements. The circled numbers show the final hardness values in a HV_{10} scale. For a heating speed of

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Table 1
Chemical composition of the 22MnB5 steel (mass%)

C	Si	Mn	P	S	Cr	Ti	B
0.24	0.27	1.14	0.015	0.001	0.17	0.036	0.003

5 K/s, the eutectoid reaction temperature point Ar_1 amounts to 722 °C and the start temperature of austenite to primary ferrite transformation point Ar_3 reaches 870 °C. After austenitization at 900 °C for 5 min followed by quenching, the microstructure becomes fully martensitic (zone M in Fig. 1); the steel lies accordingly in the ultra high strength steel grades. Primary austenite grain size (PAGS) after austenization at 900 °C for 5 min varies between 22 and 44 μm. The martensite start point M_s lies at 410 °C and the martensite finish point M_f at 230 °C. As illustrated in Fig. 1, a cooling rate greater than 30 K/s results in a fully martensitic microstructure. At lower cooling rates, bainite (zone B in Fig. 1) or even ferrite (zone F in Fig. 1) can be formed resulting in lower hardness and strength levels.

A Baehr DIL 805 deformation dilatometer was employed to create the thermo-mechanical process. Several isothermal compression and quenching tests at temperatures between 600 and 900 °C and different strain rates between 0.1 and 10.0 s^{-1} were carried out. These loading conditions are close to those appearing during hot stamping. In all of the tests, samples were austenitized at 900 °C for 5 min and quenched with rate 50 °C/s to the temperature at which the compression test is performed. An elevated temperature involves static recovery and recrystallization. To minimize these effects, the amount of time spent at elevated temperature was just along to reach uniform temperature inside the specimen. Similar precautions were taken in Ref. [10] where the deformation, temperature and strain rate sequence effects have been studied on OFHC Cu. The different thermo-mechanical processes as well as an example force and temperature evolution during isothermal compression tests are illustrated in Fig. 2.

The experimental procedure was to insert a cylindrical Rastegaev's Specimen [11], in a vacuum chamber. The geometry of the sample is illustrated in Fig. 3a. Once the austenization temperature was reached, thanks to a resistance heating, the compression was performed between SiN_2 anvils. Molybdenum foils were used to prevent the specimen sticking to the anvils and glass powder was added for lubrication. The temperature was measured by a Pt/Pt-Rh10% thermocouple welded on the specimen. The atmosphere protected first by vacuum and then argon and helium shower was employed for controlled cooling. The experimental setup from which flow curves were obtained is shown in Fig. 3b.

3. Modeling

3.1. Description

3.1.1. Molinari–Ravichandran constitutive model

Molinari and Ravichandran [9] have proposed a phenomenological constitutive model, henceforth called MR Model, based on a single internal variable δ that can be viewed as being related to a characteristic length scale of the microstructure that develops in the metal during deformation. In this model, the flow stress σ is a function of the intrinsic resistance $\hat{\sigma}_0$ of the material and the strain rate $\dot{\varepsilon}$,

$$\sigma = \hat{\sigma}_0 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^{1/m}, \tag{2}$$

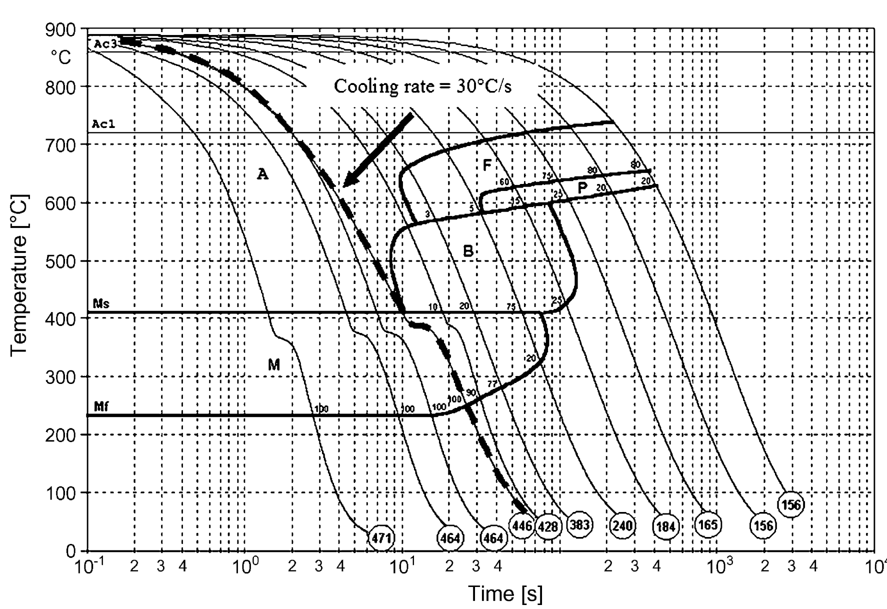

Fig. 1. CCT diagram of 22MnB5 steel austenitized at 900 °C for 5 min.