Materials and Design 62 (2014) 255–264

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Constitutive description for the design of hot-working operations of a 20MnCr5 steel grade

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ARTICLE INFO

Article history:
Received 21 March 2014
Accepted 9 May 2014
Available online 22 May 2014

Keywords:
Constitutive modeling
Hot-working
20MnCr5 steel
Work-hardening
Dynamic recovery
Dynamic recrystallization

ABSTRACT

The development of sound constitutive descriptions able to predict accurately the changes in flow stress during plastic deformation, under changing temperature and strain rate conditions is of utmost importance for the correct prediction of the mechanical response of metals and alloys, which undergo deformation under hot-working conditions. Therefore, the present work has been conducted with the aim of developing a constitutive model of such characteristics, able to describe as accurate as possible the changes in flow stress of a commercial 20MnCr5 steel, when this material is deformed at elevated temperatures and different strain rates. Particular attention has been paid to the analysis of the flow stress, work-hardening and work-softening behavior when this material is subjected to transient testing conditions, that is to say, changes in strain rate and deformation temperature in the course of plastic deformation. The constitutive description is initially developed from the analysis of the stress–strain curves obtained from axisymmetric compression tests conducted under nominal constant testing conditions, which involved the deformation of the material at temperatures in the range of 1123–1473 K and strain rates of 0.01–10 s^{-1}, up to effective strains spanning from approximately 0.6 to 1. The initial work-hardening and the subsequent work-softening behavior exhibited by the material during plastic deformation have been thoroughly characterized on a rational basis. The temperature and strain rate dependence of the yield stress, critical stress for the initiation of dynamic recrystallization, apparent saturation stress and actual steady-state flow stress have been described by means of the Sellars–Tegart–Garofalo model. The time to 50% dynamic recrystallization has also been described as a function of deformation temperature and strain rate, by means of a simple parametric relationship commonly employed for this purpose. The proposed constitutive description employs a single activation energy, whose value is close to that required for the self-diffusion of Fe in austenite, of approximately 284 kJ mol^{-1}. Further experiments involving changes in deformation temperature and strain rate have been carried out in order to validate the constitutive model. The results indicate that the proposed approach is able to describe satisfactorily the changes in flow stress, work-hardening and work-softening of the investigated material during transient testing conditions.

1. Introduction

Industrial hot-working processes are mainly characterized by the fact that, during manufacturing, the material is deformed plastically under transient testing conditions, that is to say, a situation in which the stock experiences significant changes both in deformation temperature and strain rate in the course of plastic deformation. As a consequence of this fact, the formulation of a rational constitutive description of the material able to predict as accurate as possible the changes in flow stress, as well as the

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http://dx.doi.org/10.1016/j.matdes.2014.05.011
0261-3069/

Nomenclature

Arabic symbols

A	material constant
B	material parameter (s^{-1})
D	material constant
d_0	initial austenitic grain size (μm)
d_{DRX}	dynamically recrystallized grain size (μm)
m	material constant
n_{Av}	Avrami exponent
R	universal gas constant ($J\,K^{-1}\,mol^{-1}$)
q	material constant
Q	experimental activation energy ($J\,K^{-1}\,mol^{-1}$)
Q_{DRX}	activation energy for DRX, ($J\,mol^{-1}$)
$t_{0.5}$	time for 50% recrystallization (s)
T	absolute temperature (K)
v	material constant
X_v	volume fraction recrystallized
Z	Zener–Hollomon parameter (s^{-1})

Greek symbols

α	material parameter (MPa^{-1})
ε	effective strain
$\dot{\varepsilon}$	effective strain rate (s^{-1})
$\mu(T)$	temperature-dependent shear modulus (MPa)
μ_0	shear modulus at 0 K (MPa)
$\Delta\sigma$	flow softening due to DRX (MPa)
σ	effective stress (MPa)
σ_ε	flow stress corresponding to the work-hardening and DRV curve (MPa)
σ_a	athermal stress (MPa)
$\sigma_{critical}$	critical stress for the onset of DRX (MPa)
$\sigma_y(T,\dot{\varepsilon})$	yield stress (MPa)
$\sigma_{Sat.}(T,\dot{\varepsilon})$	hypothetical saturation stress (MPa)
σ_{ss}	steady-state flow stress (MPa)
θ	work-hardening rate (MPa)
θ_0	athermal work-hardening rate (MPa)

work-hardening and work-softening processes associated with such changes, requires the fulfillment of a number of conditions.

In particular, the constitutive description should be formulated in differential form, in order to be able to update the changes in deformation temperature and strain rate before each iteration step during the integration scheme employed for the computation of the flow stress. Thus, explicit integrated expressions, which allow the computation of the flow stress as a function of the total strain imposed to the material, commonly employed for the description of the changes in flow stress during plastic deformation under constant testing conditions, would not be appropriate for describing such changes under transient testing conditions.

When structural steels are deformed under constant hot-working conditions, the flow stress curve exhibits a typical behavior as a consequence of the different microstructural processes that occur during plastic deformation, as shown in Fig. 1. At the beginning of the deformation process, the material experiences significant work-hardening and dynamic recovery (DRV). Both processes characterize the initial part of the stress–strain curve, where a continuous increase in flow stress at decreasing work-hardening rates is observed as the strain applied increases.

After reaching a critical stress, dynamic recrystallization (DRX) becomes operative as the main concurrent restoration mechanism, leading to the presence of a peak stress on the stress–strain curve and to a work-softening transient, followed by the attainment of a steady-state flow stress value. Therefore, the appropriate formulation of the constitutive description of the material would require a set of expressions in differential form able to predict the evolution of the different microstructural processes involved, in order that such a constitutive law could be employed for the analysis of deformation processes under transient testing conditions.

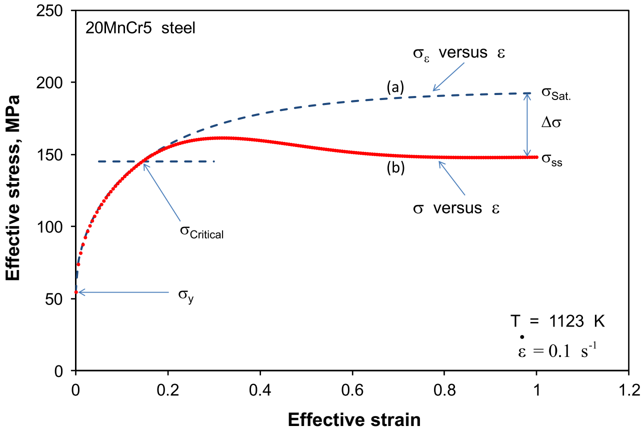

Fig. 1. Typical stress–strain curve of a 20MnCr5 steel deformed under hot-working conditions. Both the hypothetical work-hardening and DRV (σ_ε versus ε) and the actual (σ versus ε) stress–strain curves are shown on the plot.

The constitutive description and hot workability of steels, when these materials are deformed in a wide range of temperatures and strain rates, in order to analyze their behavior either during thermomechanical treatments or performance in applications as structural materials, has been extensively investigated in the past few years [1–17].

In order to accomplish this objective, different approaches for the temperature and strain rate description of the flow stress have been employed, which have included the models earlier advanced by Sellars and Tegart [18], Kocks [19], Johnson and Cook [20], Zerilli and Armstrong [21] and Follansbee and Kocks [22], among others.

However, it is important to point out that the vast majority of the constitutive descriptions developed for different steel grades have involved the analysis of the flow stress changes during extensive plastic deformation essentially under constant testing conditions, whereas only few works have examined the behavior of these materials when changes in deformation temperature and strain rate occur concurrently during the deformation process, as observed in actual hot-working operations [17,23–25].

Thus, the present investigation has been conducted in order to analyze in a rational manner the constitutive behavior of a 20MnCr5 steel grade deformed both under constant and transient hot-working conditions. Firstly, the constitutive description is derived from the results of tests carried out under constant testing conditions, which follows an improved methodology to that employed in a previous study conducted on a C–Mn steel [17].

Secondly, an analysis of the deformation of the material under varying conditions of deformation temperature and strain rate is conducted, as well as the quantitative validation of the constitutive model for describing the changes in flow stress under such deformation conditions. This aspect represents an important contribution of the present work, which could not be accomplished in our previous investigation on C–Mn steel [17].