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A novel approach for modeling the flow stress curves of austenite under transient deformation conditions

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ABSTRACT

A novel differential form of the integrated constitutive description earlier advanced by Jonas et al., for modeling the flow stress of austenite, is developed. The temperature and strain rate dependencies are introduced in the formalism through the temperature-dependent shear modulus of the material, the yield, saturation and steady-state stresses, as well as the time to achieve 50% dynamic recrystallization. The correlation between each of the above stresses and the Zener-Hollomon parameter is carried out by means of the Sellars-Tegart-Garofalo model employing the activation energy for the self-diffusion of Fe in austenite ($Q=284$ kJ mol^{-1}). The proposed formalism involves the determination of the flow stress of the material by means of the numerical integration of three differential equations. In this way, it is possible to compute the flow stress both during the work-hardening and dynamic recovery stage, as well as from the onset of dynamic recrystallization up to the work softening transient and final achievement of the steady-state stress. Therefore, it is possible to predict the flow stress curves of austenite under both sharp and ramped transient loading conditions leading to the occurrence of dynamic recrystallization, a novel feature that cannot be accomplished by means of the early advanced model.

1. Introduction

In the past few years, numerical modeling has been extensively employed for the analysis and optimization of metalworking processes. Particularly, for those forming operations conducted under hot-working conditions, such numerical tools have become very useful given the complex changes in temperature, strain rate and microstructure experienced by the material under processing. In this way, it has been possible to analyze in detail not only the geometrical changes of the stock during the different deformation steps, but also the dynamic and static microstructural evolution undergone by the material. The latter aspect is of utmost importance given the close relationship that exists between microstructure and the final mechanical properties of the material.

However, an essential aspect of different numerical tools employed for this purpose is the appropriate description of the flow stress of the material as a function of its microstructure, chemical composition and deformation conditions through appropriate constitutive descriptions. Thus, the capability of such numerical methods for conducting a precise analysis depends critically of the accuracy of such constitutive equations, which explains the interest that exists in their development and improvement under rational basis.

If the numerical models aim at analyzing hot-working processes carried out under transient loading conditions, it is essential that the formulated constitutive equation is based on valid state parameters, that is to say, parameters able to represent the microstructure of the material, which excludes the total strain applied [1]. If this condition is not fulfilled, the validity of the numerical formulation is restricted just to the analysis of deformation processes that occur under constant deformation conditions.

In the case of ferrous materials, the development of their constitutive description encompasses a large variety of alloys and types of formulations. In the past few years, one approach that has been widely employed for this purpose is the use of an Arrhenius-type model based on the hyperbolic sine relationship (referred to

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Nomenclature

Arabic symbols

A, A' material parameters
B, B_y, B_p, B_S, B_{SS} material parameters in the STG model, s^{-1}
d_0 initial austenitic grain size, μm
h athermal dislocation storage rate, m^{-2}
m, m_p, m_S, m_y, m_{SS} material parameters in the STG model
n_{Av} Avrami exponent
r dynamic recovery rate
R universal gas constant, J mol^{-1} K^{-1}
t time, s
$t_{0.5}$ time for 50% recrystallization, s
q material parameter
Q activation energy for hot-working, kJ mol^{-1}
Q_{DRX} apparent activation energy for dynamic recrystallization, kJ mol^{-1}
T Absolute temperature, K
Xv volume fraction recrystallized
v material parameter
Z Zener-Hollomon parameter, s^{-1}

Greek symbols

α material parameter in the STG model, MPa^{-1}
δ_y, δ_p, δ_S, δ_{SS} material parameters in the STG model, MPa
$d\sigma/d\varepsilon$ work-hardening or work-softening rate of the material, MPa
ε total effective strain
ε_C critical strain for the onset of DRX
$\dot{\varepsilon}$ effective strain rate, s^{-1}
μ(T) temperature-dependent shear modulus, MPa
ρ dislocation density, m^{-2}
σ flow stress of the material, MPa
σ_0 yield stress in Jonas et al. model, MPa
σ_{DRV} flow stress corresponding to the work-hardening and DRV curve, MPa
σ_a athermal stress, MPa
$\sigma_C(T, \dot{\varepsilon})$ critical stress for the onset of DRX, MPa
$\sigma_p(T, \dot{\varepsilon})$ peak stress, MPa
$\sigma_y(T, \dot{\varepsilon})$ yield stress, MPa
$\sigma_s(T, \dot{\varepsilon})$ saturation stress, MPa
$\sigma_{ss}(T, \dot{\varepsilon})$ steady-state flow stress, MPa
θ_0 work-hardening rate, MPa
Ψ difference between σ_s and σ_{ss}, MPa

as the Sellars-Tegart-Garofalo model, in the forthcoming), but assuming the strain dependence of the different parameters involved in the equation. This approach has been applied to different steels including 316L [2] and AISI 420 stainless steel (SS) [3], China low activation martensitic (CLAM) [4], as well as medium carbon and vanadium microalloyed steels [5]. Also, it has been implemented for describing the constitutive behavior of a Fe–23Mn–2Al–0.2C twinning induced plasticity (TWIP) steel under hot-working conditions [6].

Another approach commonly employed is that of the use of the Johnson–Cook [7] equation, as well as some modified form of it. This type of formulation has been recently applied to medium carbon microalloyed steels [8], among others. However, different authors have also commonly employed a modified form of the Zerilli-Armstrong equation [9], which has been applied to 20CrMo steel [10].

An alternative methodology for analyzing the deformation of austenite under hot-working conditions is based on the description of the temperature and strain rate dependence of different stress parameters of the flow stress curve, including the critical stress for the onset of DRX, as well as and the peak stress, by means of the Sellars-Tegart-Garofalo (STG) model. This approach has been applied to vanadium microalloyed [11], 9Cr–Nb–V ferritic heat resistant [12], low carbon vanadium-nitride microalloyed [13], plain carbon steels [14], 316LN SS [15], N alloyed ultra low carbon (ULC) SS [16], Fe-22Mn-0.41C-1.6 Al-1.4 Si TWIP steel [17], V microalloyed high Mn austenitic steel [18] and superaustenitic SS S32654 [19].

More recently, Dong et al., [20] attempted the development of what the authors consider a physically-based model for describing the constitutive law of a SA508-III steel, which still employs strain as state parameter. Since both the flow stress and the volume fraction recrystallized dynamically are given as a function of the strain applied to the material, the formulation does not allow updating changes in temperature and strain rate when transient deformation conditions prevail. The same features are observed in the unified internal state variable model suggested by Liu et al. [21], applied to 304 SS, as well as that proposed by Haghdadi et al. [22] for LDX 21 01 duplex SS, in which dislocation density, the dynamically recrystallized grain size or flow stress are expressed as a function of strain.

On the contrary, the unified approach advanced by Orend et al. [23] for modeling the recrystallization of steels, applied to 42CrMo4, during hot rolling is able to model both the flow stress and changes in the dynamically recrystallized grain size during deformation under transient conditions, given its independence on strain. In a similar manner, Angella [24] has conducted a physically-based analysis of the flow stress curves of an austenitic stainless steel, deformed under hot-working conditions, based on the use of Voce equation and a modified work-hardening description of the material.

In the different research works quoted above, the flow stress of the material being deformed is expressed by means of an integrated equation of the form:

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

in which the strain applied to the material appears as a state parameter in two different ways. Firstly, for the description of the work-hardening transient, at the onset of plastic deformation. Secondly, into the Avrami equation usually employed for the computation of the volume fraction recrystallized dynamically, which is of the form:

$$Xv = f\left(\varepsilon, \dot{\varepsilon}, T, d_0\right) \tag{2}$$

where d_0 represents the initial austenitic grain size.

Clearly, this type of formulations would just be limited to the computation of the flow stress when plastic deformation occurs under constant conditions of temperature and strain rate. However, these could not be employed for computing the flow stress under transient deformation conditions, that is to say, when the deformation temperature and/or strain rate vary throughout the course of deformation, since under these conditions, Eqs. (1) and (2) would not allow the updating of the $\dot{\varepsilon}$ and T values.

Therefore, given the above account, it can be clearly understood that a need for the development of rational constitutive models in which the flow stress of the material is independent of the total