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Effects of varying twist and twist rate sensitivities on the interpretation of torsion testing data

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ABSTRACT

The Nadai and Fields and Backofen expressions are widely used to convert the torque/twist data obtained during torsion testing into shear stress/shear strain curves as well as von Mises equivalent stress/equivalent strain curves. However, when employed in the conventional manner using *average* values of the twist hardening exponent *N*, they overestimate the critical strains for the initiation of twinning, dynamic transformation and dynamic recrystallization by comparison with the values determined using compression testing. By contrast, when the *local* or instantaneous values of the exponent are employed, the torsion and compression results are in good agreement. Another feature of the corrected curves is that they indicate that considerably more dynamic softening takes place during the high temperature deformation of austenite than suggested by the average *N* flow curves. It is shown that, despite the lack of work conjugacy between the torque-twist and stress–strain curves, the above expressions always lead to the correct constitutive behavior at the external radius.

1. Introduction

The Nadai expression for the shear stress in torsion was proposed in 1950 [1] and has been used ever since to deduce the shear stress/shear strain curve from torque/twist data determined in torsion experiments performed at room temperature. As it is only valid for rate-insensitive materials, it was extended in 1957 by Fields and Backofen (F & B) [2] to include the rate sensitivity and therefore to apply to materials undergoing testing at high temperatures as well. The latter is now in wide use to provide data for the prediction of rolling load, in rolling mill simulations, as well as for measuring the kinetics of dynamic and static recrystallization and precipitation [3].

According to this method, the experimental torque–twist data are converted into shear stress–shear strain form using the following expressions:

$$\tau_a = \frac{T}{2\pi a^3}(3+N+M) \tag{1a}$$

and

$$\gamma_a = \frac{a\theta}{L}. \tag{1b}$$

Here, τ_a and γ_a are the shear stress and shear strain at the outer radius a, T is the measured torque, θ is the angle of twist in radians, L is the gauge length of the specimen, and N and M are the coefficients specifying the logarithmic dependences of the torque on twist and twist rate, respectively, as given by

$$N = \left(\frac{\partial \ln T}{\partial \ln \theta}\right)\bigg|_{\dot\theta = cst} \tag{2a}$$

and

$$M = \left(\frac{\partial \ln T}{\partial \ln \dot\theta}\right)\bigg|_{\theta = cst}. \tag{2b}$$

The von Mises values are derived, in turn, from the above quantities using the relations: $\sigma_a = \sqrt{3}\tau_a$ and $\varepsilon_a = \gamma_a/\sqrt{3}$.

It is important to note that Eq. (1) is not only valid for power laws of the type $\tau = K\gamma^n\dot\gamma^m$ as commonly believed, but for *any* stress–strain relationship of the form $\tau(\gamma,\dot\gamma)$. This only excludes spatial gradient or history effects. To illustrate this remarkable property, an example is dealt with in detail in the Appendix.

The rigorous application of these equations requires determination of the *local* values of *M* and *N*, which generally vary with the angle of twist. However, because of the considerable effort involved in measuring these quantities all along the torque curve and then employing them in the calculations, it is standard practice [3] to simply use estimates of the average values of these

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coefficients, a simplification that does not generally lead to significant error.

With regard to the high temperature testing of steel samples, the most common application of torsion testing, the rate sensitivity M is usually taken as 0.13, which is a reasonable estimate of the average value, as this exponent generally falls in the interval 0.12–0.15. Over the work hardening portion of the torque–twist curve, however, N decreases from an initial value of about 0.3 or more to zero at the peak of the curve. (This will be shown below in more detail.) For convenience, an average value of 0.17 is conventionally assumed, so that the term $(M+N)$ is generally set equal to 0.3. This is the value almost universally employed to convert high temperature experimental data into stress–strain curves [3].

When the multiplier in Eq. (1) is set equal to 3.3, stress–strain curves are obtained that satisfy many technological requirements, such as the estimation of rolling load. However, when the *shape* of the flow curve must be accurately known, average values of $(M+N)$ no longer suffice. A problem that arises in such cases is that the results obtained from torque–twist curves derived using the average value of $(M+N)$ are in conflict with those determined from compression testing. It will be shown below that this problem can be resolved if the *current* or *local* rather than the average values of these coefficients are employed instead.

2. Critical strains for dynamic transformation and dynamic recrystallization

The so-called double-differentiation technique [4] is commonly used to determine the moment of initiation of a second dynamic softening mechanism (in addition to dynamic recovery). Examples of the use of this approach to determine the critical strain for the initiation of dynamic recrystallization can be found in references [5–11] and for the initiation of dynamic transformation in references [12–16]. It has also been employed to establish the critical strain for twinning in Mg [17] and Ti [18].

This method has been shown to detect the critical conditions even when *two* different softening mechanisms are induced sequentially [19–22]. In such cases, *two* sets of minima have been identified in the usual $-d\phi/d\sigma_a$ vs. σ_a plots. Examples of some stress–strain curves determined in compression [19] and torsion [20] are presented in Fig. 1a and b, respectively. The double minima obtained by differentiation are illustrated in Fig. 2a for compression testing [19] and Fig. 2b for torsion testing [20].

The compression tests were carried out at constant true strain rate on a servo-controlled MTS machine that was fitted with a Research Incorporated infrared furnace and superalloy tooling. The tests were performed inside a quartz tube and a controlled atmosphere consisting of argon +5% hydrogen was employed to prevent oxidation. Full details of the procedure followed are given in Ref. [19]. The torsion tests were conducted on an MTS-based servo-hydraulic machine, also fitted with a quartz tube and a Research Incorporated furnace and superalloy tubing [20]. In both devices, specimens were rapidly quenched after straining was terminated so that the microstructures produced could be carefully investigated.

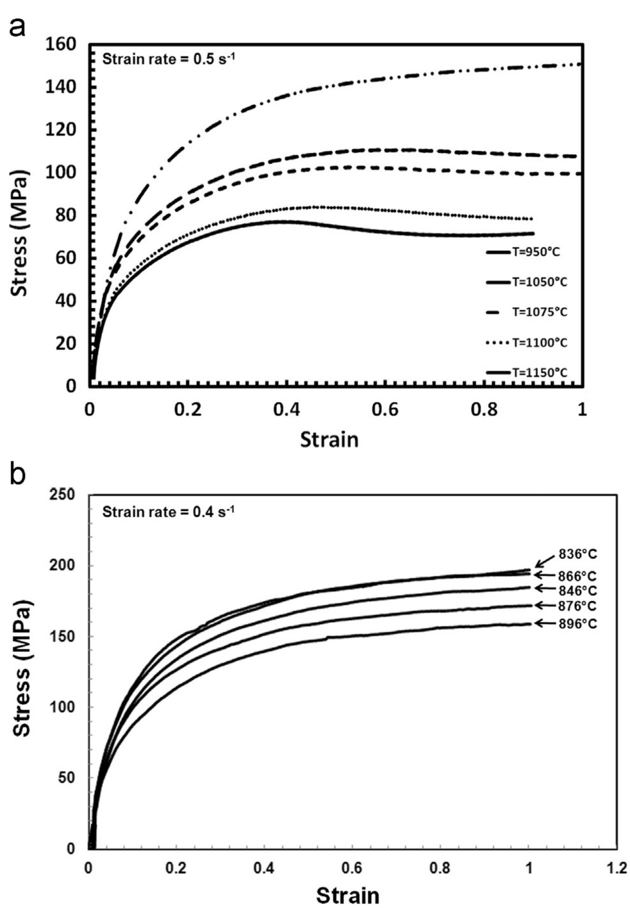

Fig. 1. (a) Hot compression flow curves determined on a 0.11C–1.1Mn–0.26Si–0.038Nb steel tested at 0.5 s^{-1} [19]. (b) Hot torsion flow curves determined on a 0.09C–1.3Mn–0.036Nb steel tested at 0.4 s^{-1} [20].

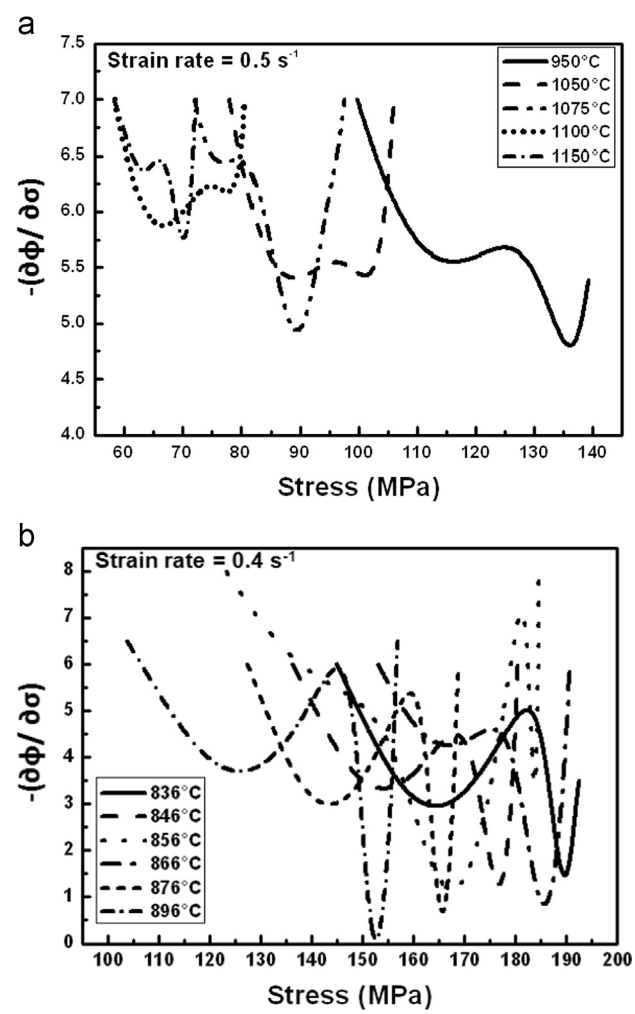

Fig. 2. (a) Dependence on stress of the stress derivative of the work hardening rate ϕ derived from the flow curves of Fig. 1a [19]. (b) Dependence on stress of the stress derivative of the work hardening rate ϕ derived from the flow curves of Fig. 1b [20].