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On the criterion for compensation to avoid elastic–plastic transients during strain rate change tests

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Abstract

Determination of the apparent activation volume and the instant strain rate sensitivity from strain rate change tests is a non-trivial task due to the short elastic–plastic transient. The flow stress can be back-extrapolated towards the incipient value, or the transient can be eliminated by a compensation technique consisting of an instant displacement introduced exactly at the moment of strain rate change. The criterion for determination of the correct amount of compensation is derived analytically. It was found that the established "experimental" criterion for the level of compensation gives an error of up to 20% in activation volume for soft tensile test rigs and affects the Haasen plot. It is shown that back-extrapolation of the stress gives the correct compensation. However, undesired changes in dislocation density may occur and modify the transients. A combination of slightly under-compensated strain rate jumps and back-extrapolation is recommended.

Keywords: Strain rate sensitivity; Plastic flow properties; Thermally activated processes; Tensile testing; Precision strain rate sensitivity technique

1. Introduction

Tensile tests with rapid changes in strain rate (strain rate change tests or jump tests) are one type of dynamic experiment from which quantities bearing information on the thermodynamic responses of deforming structures, the apparent activation volume and strain rate sensitivity, can be extracted. In order to obtain the correct values, i.e. values consistent with the theoretical derivation, the instant changes in both plastic strain rate and flow stress have to be measured with high precision. Experimentally, the change in plastic strain rate has commonly been determined as the instant change in crosshead displacement rate. Interaction between the elastic responses of the tensile test rig and that of the sample and the plastic response of the sample gives rise to an elastic–plastic transient. Due to this gradual rather than instant changes in both plastic strain rate and stress occur. The theoretically instant change in stress is then commonly estimated by back-extrapolation towards the initial flow stress. Moreover, occurrence of other transients having their origin in microstructural changes complicates correct back-extrapolation, resulting in considerable disagreement in the literature, giving results differing by a factor of two [1].

Another means of obtaining instant changes in stress and plastic strain rate is a compensation technique, the so called precision strain rate sensitivity technique [2]. By introducing a certain displacement Δx of the crosshead at the exact moment of displacement rate change one can eliminate the elastic–plastic transient and attain the desired instant change in plastic strain rate, which will result in the correct instant flow stress change. Such a device, originally designed by Basinski, has been put into practice by Champion et al. [3,4] by modification of a screw-driven tensile test rig by applying an electromagnet which can introduce displacement by enforced shortening of the system. Later a servo-hydraulic tensile test rig was modified by Carlone and Saimoto [5]. The advantage of applying a compensation is not only that it avoids the elastic–plastic transient,

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but also prevents other relaxations of the dislocation structure occurring simultaneously. The higher the temperature the greater the challenge becomes.

The compensation technique has been extensively used for precise measurement of strain rate sensitivity in order to eliminate the elastic–plastic transient [2,6–10]. Recently, Curtin [11] suggested a new interpretation of the Haasen plot for solute-strengthened alloys based on a wide range of such experiments. Diak et al. [2] presented a comprehensive review of the use of this technique, including an extensive collection of examples of under-compensated, ideally and over-compensated tests at various temperatures. The "experimental" criterion for ideal compensation was formulated by Diak et al. [2] as a "load drop to a level that remains constant during straining at the new strain rate, before work hardening intervenes…". This means that in order to obtain the correct amount of compressive displacement to obtain the ideal compensation for a given strain and strain rate one should vary the amount of compensating tool displacement until zero hardening occurs, i.e. a "plateau" in the stress can be observed. In other works [6,7] "the criterion for ideal compensation is assessed to be 90% of the load drop measured upon strain rate change", meaning 90% of the estimated change in load. This slight under-compensation was necessary since at higher temperatures dynamic recovery introduced stress relaxation. However, regardless of the relaxation phenomenon, the theoretical criterion for correct compensation has nowhere been clearly stated. The aim of this article is to state this clearly, supported by a mathematical proof. The error in activation volume and strain rate sensitivity using the "experimental" criterion is discussed.

2. Elastic–plastic transient

A tensile test might be regarded as a serial system of an elastic tensile test rig and an elastic–plastic sample. A short-range transient gradual change in stress occurs if a sudden change in the total displacement rate of this system is introduced. The total displacement rate of the whole system can be written as the sum of the displacement rates of the elastic test rig $\dot{x}_{tool}$ and the elastic–plastic sample $\dot{x}_{sample}$,

$$\dot{x} = \dot{x}_{sample} + \dot{x}_{tool} = L(\dot{\varepsilon}^{pl} + \dot{\varepsilon}^{el}) + \frac{\dot{F}}{K} = L\dot{\varepsilon}^{pl} + L\frac{\dot{\sigma}}{E} + \frac{\dot{\sigma}A}{K}$$
$$= \frac{L}{M}\dot{\gamma}^{pl} + \dot{\tau}C \quad (1)$$

where $C = A \cdot M\left(\frac{L}{EA} + \frac{1}{K}\right)$ is the effective compliance of the whole elastic part of the system. The resolved shear stress τ is related to the macroscopic normal stress through the Taylor factor M as $\sigma = M\tau$. Further, $\dot{\gamma}^{pl}$ is the crystallographic shear strain rate related to the macroscopic plastic strain rate $\dot{\gamma}^{pl} = M\dot{\varepsilon}^{pl}$, A is the cross-section of the specimen, L the specimen length, E is the Young's modulus of the specimen and K is the elastic constant of the test rig, including mechanical connections. The kinetic equation linking the plastic strain rate $\dot{\gamma}^{pl}$ and the rate-sensitive (thermal) part of the total stress provides a complete set of equations and the transient behaviour of stress with time $\tau(t)$ can be derived. This was first done by Mecking [12] assuming the following simplifications:

1. the activation volume is constant during the plastic strain rate change;
2. no microstructure evolution;
3. the forest dislocation density is constant (the strain hardening equals zero);
4. the mobile dislocation density is constant.

For a strain rate change test the first assumption listed is valid, since the change in stress (caused by the change in plastic strain rate) is low, resulting in almost no change in the activation volume [1]. Then the Gibbs activation energy can be linearized around the value of the stress τ_1 just before the strain rate change as $\Delta G(\tau) = \Delta G(\tau_1) - V(\tau - \tau_1)$, where V is an apparent activation volume. However, Wielke [13] concluded from numerical calculations that when applying any physically reasonable non-linear dependency $\Delta G(\tau)$ including the power-law $\dot{\gamma}^{pl} \approx \tau^m$ the transient curve $\tau(t)$ does not differ much from one derived analytically for linearized $\Delta G(\tau)$. The more general case of constant rate-independent strain hardening $h = d\tau/d\gamma^{pl}$ was later included in an analytical derivation by Wielke [13]. Subsequent to an instant strain rate change at a plastic strain γ_1^{pl} and stress τ_1 the plastic strain rate is given by the kinetic equation:

$$\dot{\gamma}^{pl} = \dot{\gamma}_0 \exp\left(\frac{\Delta G(\tau)}{kT}\right)$$
$$= \dot{\gamma}_0 \exp\left(\frac{\Delta G(\tau_1) - V(\tau - \tau_1 - h(\gamma^{pl} - \gamma_1^{pl}))}{kT}\right) \quad (2)$$

Note that h is the slope of the stress–strain curve at the strain where the $\dot{x}$ changed. Such a linearization of the curve is a very good approximation during a short transient. The mobile dislocation density is assumed to be constant in order to make analytical derivation possible. Possible changes in the mobile dislocation density which could explain the deviations of typical experimental curves showing short yield point transients from the "ideal" one were discussed by Schoeck [14].

If we assume that at time $t = 0$ the total displacement rate change occurs instantly from $\dot{x}_1$ to $\dot{x}_2$, Eqs. (1) and (2) can be integrated using the initial conditions:

$$\dot{x}(0) = \dot{x}_2$$
$$\Delta\tau(0) = 0$$
$$\dot{\gamma}^{pl}(0) = \dot{\gamma}_1^{pl} = \frac{M\dot{x}_1}{L} \cdot \frac{1}{1 + \frac{hMC}{L}} \quad (3)$$

As in the earlier works, the small changes in A and L during the transient can safely be neglected. A solution for the change in stress $\Delta\tau(t) = \tau - \tau_1$ as a function of time is (Eq. (8) in Wielke and Schoeck [13])