# Modeling of strain rate history effects in BCC metals

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## Abstract

We propose a new material modeling approach for BCC metals, based on the addition of an internal state variable for modeling the strain rate history effects. The new internal state variable, $r_{ISV}$, has the dimensions of the strain rate and associates the material microstructural state at a given plastic strain to an equivalent state that would be produced by a constant strain rate test of magnitude $r_{ISV}$. The proposed formulation accounts for the strain rate history effects where the transients due to strain rate jumps are significant. The proposed concept is also applicable for modeling discontinuous yielding phenomena and peak forces during impact.

*Keywords:* Strain rate sensitivity; Strain rate history, BCC metals

## 1. Background

The complexity of material characterization under dynamic loading [1] is compounded with the difficulties of filtering of equipment artifacts from the genuine material behavior. This filtering is especially difficult for materials that exhibit pronounced transient effects during the onset of yielding or rapid change in loading rate.

The transient effects during the loading rate change have been the subject of research over the last several decades. In general, two theories were put forward for addressing the transient material response under sudden changes in loading rate. The first attributes the transient behavior to the stiffness of the testing equipment and the sample, while the second characterizes the observed material response as the fundamental property of the material. Experimental results obtained on very stiff testing equipment with feedback control favor the later explanation. Earlier results with shocked material [2] and dynamic torsion bars [1] also support the notion of significant material microstructure evolution during the loading rate jumps. The delay–yield phenomenon and its rate dependence also fall into the same general category. These phenomena have been satisfactorily explained by the dislocation theory [3], which was used in engineering simulations to improve modeling of the peak impact forces.

In the earlier studies [4], strain rate history effects in the face-centered closest packing (FCC) and the body centered cubic (BCC) metals have been studied based on the concept of fading memory. Based on this concept, the material loses its memory of the previous strain rate gradually within the duration of the current loading rate. Other models that are based on dislocation mechanics account for the strain rate history through evolution of its internal variables. Because many use the strain rate jump tests for investigation of superposition of strengthening mechanisms and strain rate sensitivity evolution with the strain, they incorporate strain rate history effects although not as their primary scope. Recent investigation [5] of the ability of modern micromechanics-based material models to simulate the strain rate jump tests found that the models could not accurately fit all the transients.

## 2. Transient stresses in BCC metals

Several major differences between the deformation characteristics of FCC and BCC alloys exist [8]. Contrary to the FCC metals, the primary short-range obstacle to dislocation motion is the Peierls-Nabarro frictional stress, and the stored dislocations behave as long-range obstacles such that the hardening rate is not strongly affected by the strain rate. Experiments on BCC metals [6,7] indicate that the slip becomes finer, and that mobile dislocation density increases, with increasing strain rate. In the BCC metals the mobile dislocation density increases rapidly with the applied strain and

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reaches an equilibrium state that gives the lowest stress at a given strain rate. This implies the existence of an attractor state for each applied strain rate, toward which the current material state will eventually evolve if the loading is continued. In other words, the consequence of the existence of an attractor state is that there exists a unique characteristic strain rate for which the material microstructural state would be in equilibrium.

The material model proposed in this paper introduces a new scalar internal state variable (ISV), $r_{\mathrm{ISV}}$, associated with the characteristic strain rate of the material microstructural state. The stress due to the strain rate transition is superimposed on to the base stress that would otherwise be obtained if the strain rate changes were not accounted for. Stress enhancement due to the difference between the applied and characteristic strain rate, ISV, is modeled by a viscous rheological element, and is based on the transients observed in experiments. The evolution law of the strain rate ISV is such that it will eventually saturate to the applied strain rate according to the fading memory rule.

## 3. Model formulation

Figure 1 presents the rheological scheme for the elasto-visco-plastic material model. The stress balance is written in the form of a linear differential (Eq. (1)) that can be solved in closed form.

$$\eta\alpha^{\frac{1}{n}}\left(\frac{d\varepsilon_p}{d\varepsilon}\right)^{\frac{1}{n}}+\sigma_y+k_0\varepsilon_p-E(\varepsilon-\varepsilon_p)=0,\varepsilon_p\left(\frac{\sigma_y}{E}\right)=0 \qquad (1)$$

The associated stress–strain curves corresponding to Eq. (1) for different constant strain rate tests are shown in Fig. 2. The material response in Fig. 2 indicates that Eq. (1) is not suitable for modeling the effect of stress transients during the early loading.

Figure 3 presents the scheme of the proposed model, where a new element has been introduced to account for the evolution of an internal microstructural state that accommodates the strain rate jump. As mentioned earlier, in BCC metals, the material's structure responsible for accommodating the imposed strain rate will gradually transition between its current equilibrium state described by $r_{\mathrm{ISV}}$ to the state that corresponds to the imposed external strain rate. For simplicity we have used the imposed total strain rate as the target rate. Variable $r_{\mathrm{ISV}}$ represents the characteristic strain rate variable for the current material state. The element resembles a viscous element as it is proportional to a difference of two rate terms. The new equilibrium equation is

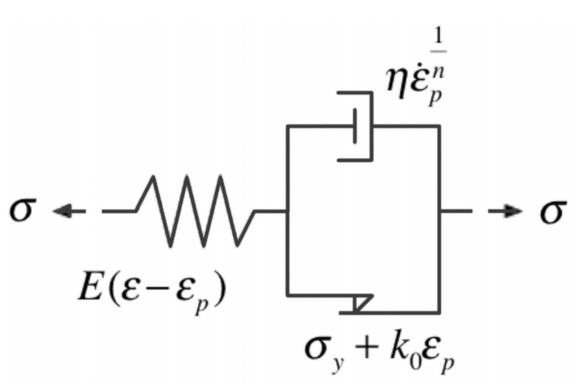

Fig. 1. Elasto-visco-plastic material.

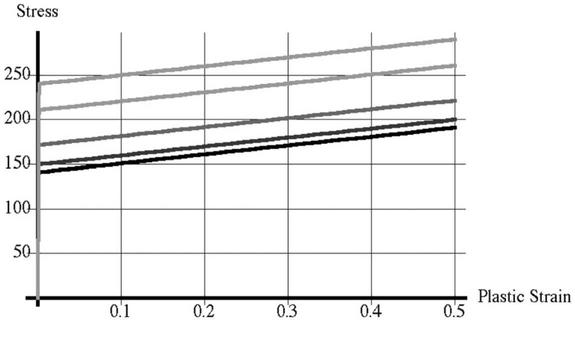

Fig. 2. Stress–strain curves (strain rates 0.1, 1, 10, 50, 100/s, stress in MPa).

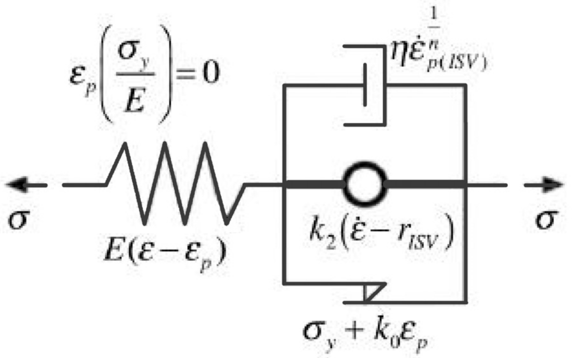

Fig. 3. Elasto-visco-plastic material with strain rate history effect.

$$E(\varepsilon-\varepsilon_p)=\eta\dot{\varepsilon}_{p(ISV)}^{\frac{1}{n}}+\sigma_y+k_0\varepsilon_p+k_2(\dot{\varepsilon}-r_{ISV})=0,$$
$$\varepsilon_p\left(\frac{\sigma_y}{E}\right)=0 \qquad (2)$$

The initial value for $r_{\mathrm{ISV}}$ can be estimated from the experimental data as the highest constant strain rate that does not produce noticeable stress transients (overshoots) and is denoted as $r_{\mathrm{ISV}}{}^0$. The evolution law for $r_{\mathrm{ISV}}$ (fading of memory of the previous strain rate) is assumed to be in the exponential form with a time relaxation constant $\tau$:

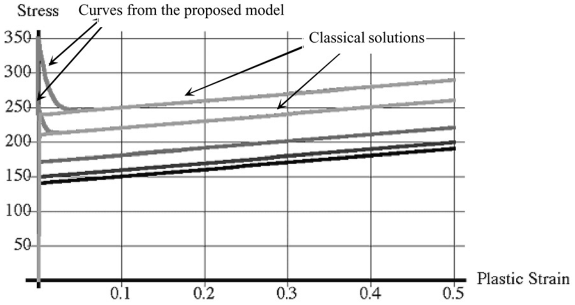

Fig. 4. Stress–strain curves for model with strain rate history effect (strain rates 0.1, 1, 10, 50, 100/s).

$$\dot{r}_{ISV} = -\frac{1}{\tau}\left(r_{ISV} - \dot{\varepsilon}\right) \tag{3}$$

We restrict the analysis to the initial loading only so that we can integrate Eq. (3) analytically:

$$r_{ISV} = \dot{\varepsilon} + \left(r^{0}_{ISV} - \dot{\varepsilon}\right)e^{-\frac{t}{\tau}} \tag{4}$$

Parameter $\tau$ in Eq. (3) can be estimated based on the duration of the transients in experiments. Another obvious choice for the evolution law would be to base it on plastic strain increment. However, in the present study, Eq. (2) is selected because it can be solved analytically. Fig. 4 presents the solutions for imposed constant strain rate tests, assuming that ${r_{\mathrm{ISV}}}^{0} = 0$.

The curves from the proposed model in Fig. 4 include the stress enhancements due to the transition of the internal state component responsible for strain rate accommodation. The overall trends in Fig. 4 correspond favorably to the trends observed in experiments. The duration, shape and magnitude of the transients can be modified using a different evolution law for $r_{\mathrm{ISV}}$ and a more complicated rheological element.

## 4. Conclusion

The paper proposes a new internal state variable corresponding to the characteristic strain rate associated with the material's current microstructural state for describing the strain rate history effects. The new ISV is added to the classical elasto-visco-plastic model to illustrate its ability to model the jumps in the applied strain rate.

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