ADVANCED CONSTITUTIVE RELATION FOR NUMERICAL APPLICATIONS: MODELING OF STEELS IN A WIDE RANGE OF STRAIN RATES AND TEMPERATURES

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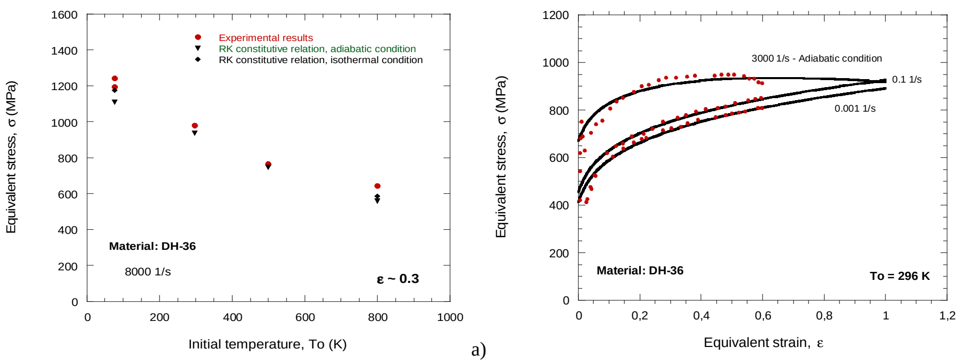
Abstract
Among many constitutive relations implemented so far in a number of commercial computer codes, the most advanced are those that include strain hardening and also strain rate and temperature sensitivities of flow stress. Almost all of them are based on the concept of the Mechanical Equation of State **(MES)**. One of such modern constitutive relations that have been proposed by Rusinek and Klepaczko **(RK)**, [1], include an extended flexibility in an accurate approximation of materials behavior over wide range of plastic strain, strain rates and temperatures. The RK constitutive relation has only eight fundamental constants and the meaning of each constant is analyzed in detail in this paper. The main goal of this contribution is to demonstrate some recent applications of the RK constitutive relation in solving a wide variety of complex dynamic boundary value problems, for example perforation and many others, using the Finite Element (FE) method.

1. Introduction

Metals and alloys used in engineering fields show different mechanical behavior depending on the strain rate and temperature which they are subjected to. The implementation of advanced structural materials in the automotive, aeronautical, metalworking and other industries created the need to introduce more advanced constitutive relations for engineering applications. Thus, the constants required to define the material behavior must be easily identifiable, but at the same time the material response under complex stress states must be correctly predicted. For example, in the case of high strength steels as Weldox, DH-36 or TRIP, that are widely used in civil, naval and automotive industries, the thermal coupling in form of adiabatic heating cannot be neglected, especially at high strain rates and large deformations, Fig. 1. The adiabatic increase of temperature leads to thermal softening and plastic instabilities as precursors of failure.



a) b)

Fig. 1. Comparison between experimental results [2] and RK model; a- Temperature sensitivity, b- Strain rate sensitivity

It can be concluded that a sophisticated constitutive relation must cover large strains, $0 \le \bar{\varepsilon}_p \le 1.0$, a wide range of strain rates, $10^{-4}s^{-1} \le \dot{\bar{\varepsilon}}_p \le 10^4 s^{-1}$, and an adequate range of absolute temperatures, $200K \le T \le 0.5T_m$, where T_m is the melting temperature. However, to cover such ranges of the variables $\left(\bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p, T\right)$ using experimental techniques is not an easy task. Thus, many experimental results in the form $\bar{\sigma} = f\left(\bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p, T\right)$, where $\bar{\sigma}$ is the true stress in tension/compression, are frequently different for the same material. Therefore, the first step is evaluation of material constants which define adequate constitutive relation is an analysis of the mean experimental data.

2. Constitutive relation with strain rate and temperature dependence of strain hardening

An advantage to predict the material behavior when subjected to high temperature and high strain rate is an assumption of strain hardening exponent n in general form $n = n_0 f(\dot{\bar{\varepsilon}}_p, T)$, where f is the weigh function. The rate and temperature sensitive strain hardening was introduced into constitutive modeling for the first time in an open publication by Rusinek and Klepaczko in 2001, [1]. It was assumed in addition that the flow stress has two components called the internal and the effective stress. This concept due to Seeger is based on the theory of dislocations. The internal stress component accounts for the multiplication and storage of the immobile dislocations producing strain hardening. The total stress is therefore the sum of these two components, the internal stress σ_μ and the effective stress σ^* respectively

$$\sigma(\bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p, T) = \frac{E(T)}{E_0}\left[\sigma_\mu(\bar{\varepsilon}_p \dot{\bar{\varepsilon}}_p, T) + \sigma^*(\dot{\bar{\varepsilon}}_p, T)\right] \quad (1)$$

Where $E(T)$ is the temperature-dependent Young's modulus, E_0 is the Young's modulus at $T = 0\,K$. The effective stress component is related to the evolution of the mobile dislocation density leading to rate and temperature sensitivity of flow stress. Within the framework of the MES the RK constitutive relation, [1], is given by

$$\sigma = B(\dot{\varepsilon}, T)(\varepsilon_0 + \varepsilon_p)^{n(\dot{\varepsilon}, T)} + \sigma_0^*\left\langle 1 - D_1\left(\frac{T}{T_m}\right)\log\left(\frac{\dot{\varepsilon}_{max}}{\dot{\varepsilon}}\right)\right\rangle^{m^*} \quad (2)$$

Where $B(\dot{\bar{\varepsilon}}_p, T)$ is the modulus of plasticity, $n(\dot{\bar{\varepsilon}}_p, T)$ is the rate and temperature dependent strain hardening exponent, σ_0^* is the threshold of the effective stress at T = 0 K, D_1 and T_m are respectively the material constant and the melting temperature. Typical value for the strain rate upper limit is $\dot{\varepsilon}_{max} \approx 10^7 s^{-1}$. Because the set of those constitutive equations is assumed to be applied also within a wide range of temperatures, assumed temperature values vary in the range $50K \le T \le T_m / 2$. Two limits in Eq.(2) are imposed: if <*> < 0 then <*> = 0, also if n < 0 then n = 0. The two stress components are corrected for the temperature-dependent rigidity of the crystalline lattice via the temperature variations of Young's modulus E(T) as reported originally by Klepaczko, [3]. Moreover, a stress correction for the adiabatic increase of temperature is described using the equation of energy balance. Theory of J_2 plasticity for isotropic behavior combined with the implicit integration scheme for finite element simulation is the base for a wide range of applications, as shown in Fig.2. An original implicit algorithm developed by Zaera and Fernández-Sáez, and reported in [4], is used to solve incrementally the set of RK constitutive equations defined above. With this algorithm many dynamic problems can be simulated by finite element codes. The material constants of the RK constitutive relation are identified so far for more than twenty materials, mostly steels used in the aeronautical and automotive industries.

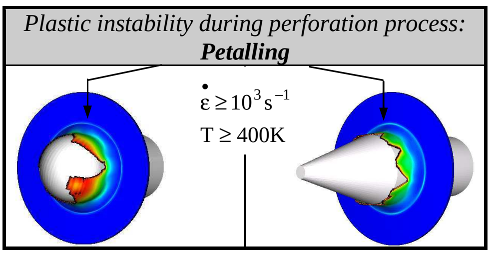


Fig. 2. Numerical simulation of perforation process using RK model to describe behavior of DH-36 steel

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