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Acta Materialia 53 (2005) 5387–5400
Acta MATERIALIA
www.actamat-journals.com

Analysis of inertia and scale effects on dynamic neck formation during tension of sheet steel

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Received 30 June 2005; received in revised form 10 August 2005; accepted 10 August 2005
Available online 6 October 2005

Abstract

It is well known that a specimen for impact testing must be optimized in terms of its dimensions. The main reason is to reduce strain gradients due to the effects of elastic–plastic wave propagation. On the other hand, when a split Hopkinson bar in tension is applied, the net displacement of the specimen ends is very limited, usually from 2.0 to 3.0 mm. Thus, to reach a maximum strain of 0.5 the specimen length must be reduced in dimensions from 4.0 to 6.0 mm. Consequently, small diameters or lateral dimensions and lengths must be applied to assure one-dimensional deformation. Such small lengths substantially perturb the determination of real material behavior. So the main motivation of this study was to perform a systematic analysis, numerical and analytical, to find differences in the behavior of short and long specimens loaded in impact tension. The finite element code ABAQUS/Explicit has been used to simulate several specimen lengths from 10 to 40 mm submitted to impact velocities ranging from 10 to 100 m/s.

Keywords: Constitutive relation; Dynamic tension; Normalization; Plastic instability; Numerical simulations

1. Thermoviscoplastic modeling

To study the dynamic processes of plastic deformation in sheet metals, a well defined constitutive relation has earlier been proposed. Several processes of fast deformation have been previously studied by applying that relation: perforation [1], double shear by direct impact [2], the Taylor test and fast tension test [3]. With the constitutive relation, Eq. (1), the effect of temperature and strain rate on the flow stress can be studied and analyzed. It is clear that the adiabatic increase of temperature has a substantial effect on the flow stress and it induces a decrease in the ultimate tensile stress. In order to describe precisely the behavior of materials at high strain rates and temperatures, the equivalent stress $\bar{\sigma}$ needs to be taken as the sum of two components σ_μ and σ^* which are, respectively, the internal and the effective stress. The first component is directly related to the strain hardening of the material and the second defines the contribution due to the thermal activation (a combination of temperature and strain rate). The constitutive relation can be written in terms of equivalent scalar quantities:

$$\bar{\sigma}(\bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T) = \frac{E(T)}{E_0}[\sigma_\mu(\bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T) + \sigma^*(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)], \tag{1}$$

where $\bar{\varepsilon}^{\mathrm{p}}$ is the equivalent plastic strain, T is the absolute temperature, E_0 is the Young's modulus at $T = 0$ K and $E(T)$ is the evolution of the modulus as a function of temperature. Eq. (1) is based to some extent on physical considerations [2]. The explicit expressions for both stress components are given below:

$$\sigma_\mu(\bar{\varepsilon}^{\mathrm{p}}, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T) = B(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)(\varepsilon_0 + \bar{\varepsilon}^{\mathrm{p}})^{n(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)}, \tag{2}$$

where $B(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)$ and $n(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)$ are the modulus of plasticity and the strain hardening exponent, respectively. These quantities, defined by Eqs. (3) and (5), respectively, take into account the experimental observations that the strain hardening itself depends on temperature and strain rate.

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doi:10.1016/j.actamat.2005.08.019

$$n(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T) = \left\langle n_0\left(1 - D_2\left(\frac{T}{T_{\mathrm{m}}}\right)\log\left(\frac{\dot{\bar{\varepsilon}}^{\mathrm{p}}}{\dot{\varepsilon}_{\min}}\right)\right)\right\rangle \quad \text{with} \quad \dot{\varepsilon}_{\min} \leqslant \dot{\bar{\varepsilon}}^{\mathrm{p}} \leqslant \dot{\varepsilon}_{\max}, \tag{3}$$

where n_0 and D_2 are material constants, T_{m} is the melting point, $\dot{\varepsilon}_{\min}$ is the minimum strain rate which defines the quasi-static stress–strain relation, $\dot{\varepsilon}_{\max}$ is the maximum limit of strain rate. where $\langle\bullet\rangle$ are the MacCauley brackets:

$$\langle\bullet\rangle = \begin{cases} \bullet & \text{if } \bullet \geqslant 0, \\ 0 & \text{if } \bullet < 0 \end{cases} \tag{4}$$

such that negative values of the hardening exponent are not allowed.

For the ES mild steel (C: 0.03%, S: 0.011%, Mn: 0.203%, Al: 0.054%, Cr: 0.041%, Ni: 0.018%) [1,2] analyzed in this paper, the strain-hardening exponent n substantially changes with strain rate and temperature, particularly in the adiabatic conditions [2]. This mild steel is used for deep drawing applications due to its large ductility. Moreover, the effective strain rate $\dot{\bar{\varepsilon}}^{\mathrm{p}}$, which corresponds to the complete transition into adiabatic conditions of deformation is estimated as $\dot{\bar{\varepsilon}}^{\mathrm{p}} \approx 10\ \mathrm{s}^{-1}$. For strain rates higher or equal to $10^2\ \mathrm{s}^{-1}$, a significant temperature increase ΔT is observed with plastic deformation and at the same time an intensification of the thermal softening of the material occurs. The process of plastic deformation is then coupled with temperature as will be shown later. The formula for $B(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)$ is a function of the homologous temperature modified by strain rate [3]:

$$B(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T) = \left\langle B_0\left(\left(\frac{T}{T_{\mathrm{m}}}\right)\log\left(\frac{\dot{\varepsilon}_{\max}}{\dot{\bar{\varepsilon}}^{\mathrm{p}}}\right)\right)^{v}\right\rangle \quad \text{with} \quad \dot{\varepsilon}_{\min} \leqslant \dot{\bar{\varepsilon}}^{\mathrm{p}} \leqslant \dot{\varepsilon}_{\max}, \tag{5}$$

where B_0 is the material constant and v is the temperature sensitivity (usually negative).

The explicit form of the effective stress σ^*, given by Eq. (6), is similar to the Arrhenius relation which describes the kinetics of thermally activated processes:

$$\sigma^*(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T) = \left\langle \sigma_0^*\left(1 - D_1\left(\frac{T}{T_{\mathrm{m}}}\right)\log\frac{\dot{\varepsilon}_{\max}}{\dot{\bar{\varepsilon}}^{\mathrm{p}}}\right)^{1/m}\right\rangle \quad \text{with} \quad \dot{\varepsilon}_{\min} \leqslant \dot{\bar{\varepsilon}}^{\mathrm{p}} \leqslant \dot{\varepsilon}_{\max}, \tag{6}$$

where σ_0^* is the effective stress at $T = 0$ K, D_1 is the material constant and $m^* = 1/m$ is the coefficient characterizing the temperature and strain rate sensitivity. In adiabatic conditions the quantities that are functions of temperature are coupled via Eq. (7), which gives the increment of temperature $\Delta T_{\mathrm{adiabatic}}$ due to the plastic work converted into heat [30].

The adiabatic increase of temperature triggers the thermal softening phenomenon and reduces the rate of strain hardening

$$T_{\mathrm{adiabatic}} = T_0 + \Delta T_{\mathrm{adiabatic}},$$

$$T_{\mathrm{adiabatic}} = T_0 + \frac{\beta}{\rho C}\int_{\varepsilon_{\mathrm{e}}}^{\bar{\varepsilon}^{\mathrm{p}}} \sigma(\xi, \dot{\bar{\varepsilon}}^{\mathrm{p}}, T)\,\mathrm{d}\xi, \tag{7}$$

where β is the Taylor–Quinney coefficient of plastic work converted into heat, ρ is the density of material and C is the specific heat at constant pressure. In our case C is constant but generally it is a function of temperature [28,29].

The material constants used to describe the thermoviscoplastic behavior of ES steel are given in [1–4]. It is commonly observed that an increase of strain rate causes an increase of the yield and flow stress. The logarithmic rate sensitivity m is very important in modeling of the thermoviscoplastic behavior of materials. This parameter, defined by the following relation, Eq. (8), is close to $m \approx 0.02$ for the sheet of mild steel at low strain rate for room temperature

$$m(T) = \left.\frac{\partial \log \sigma}{\partial \log \dot{\bar{\varepsilon}}^{\mathrm{p}}}\right|_{\bar{\varepsilon}^{\mathrm{p}}, T} \quad \text{with } m \geqslant 0. \tag{8}$$

The experimental results reported in [4] have permitted the determination of the logarithmic strain rate sensitivity for ES steel. For the range of low strain rates $10^{-4} \leqslant \dot{\bar{\varepsilon}}^{\mathrm{p}} \leqslant 10^{-1}\ \mathrm{s}^{-1}$, the strain rate sensitivity is $m = 0.023$ and increases to $m = 0.05$ for the range of high strain rates $1 \leqslant \dot{\bar{\varepsilon}}^{\mathrm{p}} \leqslant 10^3\ \mathrm{s}^{-1}$ for strain level $\bar{\varepsilon}^{\mathrm{p}} = 0.1$. However, at larger plastic strain a decrease of the strain rate sensitivity is induced by the thermal softening of the material; this effect is more important when the strain rate increases. It can be stated that the apparent strain rate sensitivity which is coupled with temperature strongly depends on the plastic work accumulated during plastic deformation and converted into heat. In general the thermal softening of the stress causes this phenomenon. The value of the apparent strain rate sensitivity can change at high strain rates with the specimen geometry as will be shown later after the numerical analysis, more precisely for a short specimen. If the process of thermal softening resulting from the coupling $\dot{\bar{\varepsilon}}^{\mathrm{p}} - T$ is not well defined, the process of plastic deformation cannot be studied correctly. In our case, the strong coupling $\dot{\bar{\varepsilon}}^{\mathrm{p}} - T$ inducing a thermal softening of the material is partly caused by variation of the strain hardening exponent $n(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T)$, Eq. (3). When temperature or strain rate increases then $n(\dot{\bar{\varepsilon}}^{\mathrm{p}}, T) \to 0$ which is commonly observed in dynamic tests.

Several constitutive equations have been proposed in the past. Those proposed by Cowper and Symonds [5] and Johnson and Cook [6] are empirical, and in that due to Zhao [7], an extension of the Tanimura formulation [47], temperature effects are not included. Zerilli and Armstrong [9] proposed a constitutive relation coupled with temperature and with some background of materials science. Next, a comparison between some of these constitutive relations for sheet steel ES is performed, Fig. 1. Apparently, a relatively good agreement with experiment for small strains and constant temperature is found for the relation proposed by Zhao. A simple reason for this agreement is the additive form of the relation where an increase of strain rate causes a translation of strain–stress curve toward higher stresses. The disadvantage of all phenomenological relations formulated at constant temperature is the very limited range of applications of all numerical simulations at high