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FLOW LOCALIZATION AND FRACTURE IN MATERIALS EXHIBITING STRUCTURAL SUPERPLASTICITY

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Instability in Superplastic Materials

The resistance to necking of superplastic materials is attributed to the strain-rate sensitivity of the flow stress (1,2). If a constitutive equation of the form

$$\sigma = K\varepsilon^n \dot{\varepsilon}^m \quad (1)$$

is assumed plastic deformation remains stable as long as

$$n/\varepsilon + m \geqslant 1, \text{ then } \varepsilon \leqslant n/(1-m) \quad (2)$$

Because $m < 1$ it is expected that the high rate-sensitivity provides a resistance to neck growth. When a neck begins to form there is a local increase in stress necessary to continue necking because of the effect of strain-rate sensitivity.

Recently there has been discussion of the effects of defects or inhomogeneities on plastic stability. These approaches have been reviewed by Nichols(3) and Lin and co-workers(4). It has been shown that Hart's original criterion(1) can be expressed in terms of a fluctuation in cross-section whose origin can be either geometrical or can develop during deformation.

For an irreversible system, the state variables are not sufficient to define the state uniquely, therefore additional intrinsic variables have to be introduced into the constitutive equation. Based on this approach Valanis proposed his so-called endochronic theory(5). Here a general form of constitutive equation for a material would take into account the effects of strain, strain rate, temperature and metallurgical variables on the flow stress. In this case the flow stress may be written as some function of ε, $\dot{\varepsilon}$, T and N, where N is an intrinsic variable representing all metallurgical variables which influence the flow stress such as: grain size, plastic anisotropy and micro-mechanisms of plastic deformation. History effects can be taken into account, in principle, through the variable N. Inevitably, though, to avoid complexity in the derivation of constitutive equations simplifying assumptions must be made.

It is assumed here, for simplicity, that the grain size, L, is the only important metallurgical variable in relation to the flow stress, then the stress may be written as:

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T, L) \quad (3)$$

From the maximum load condition for the onset of tensile necking, it follows that

$$\left(\frac{\partial\sigma}{\partial\varepsilon}\right)_{\dot{\varepsilon},T,L} + \left(\frac{\partial\sigma}{\partial\dot{\varepsilon}}\right)_{\varepsilon,T,L} \cdot \frac{d\dot{\varepsilon}}{d\varepsilon} + \left(\frac{\partial\sigma}{\partial T}\right)_{\varepsilon,\dot{\varepsilon},L} \cdot \frac{dT}{d\varepsilon} + \left(\frac{\partial\sigma}{\partial L}\right)_{\varepsilon,\dot{\varepsilon},T} \cdot \frac{dL}{d\varepsilon} - \sigma = 0 \quad (4)$$

It is reasonable to assume that metallurgical changes cause the observed hardening effect of the strain. It may also be assumed that this strain hardening effect can be divided into two separate causes: the grain size changes and other metallurgical changes. It is then possible to write

$$\varepsilon^n = K_1 (L/L_o)^a \varepsilon^{n_1} \quad (5)$$

Substituting this into equation (1) partially differentiating and substituting into equation (4) provides

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$$\varepsilon_i = \frac{n}{\left\{1 - \left(\frac{\partial\sigma}{\partial T}\right)_{\varepsilon,\dot{\varepsilon},L} \cdot \frac{Ak}{\rho c} - m\,\frac{d\ell n\,\dot{\varepsilon}}{d\,\varepsilon}\right\}} \tag{6}$$

where we have substituted for the rate of increase of temperature with strain the following expression(6)

$$\frac{dT}{d\varepsilon} = \frac{Ak\sigma}{\rho c} \tag{7}$$

Here A is the fraction of the plastic work converted into heat ($A \sim 0.9$) $k = 1$ for adiabatic deformation and $k < 1$ for non-adiabatic conditions, ρ is the density and c the specific heat, k can be shown to depend on $b/\sqrt{\kappa t}$ where b is the thickness of the plastic zone, κ is the thermal diffusivity and t the time of flow.

Depending on the mechanical and physical properties of the metal under consideration the effect of thermal softening during plastic deformation may well be the development of thermoplastic shear instability(7).

Equation (6) shows the effects of temperature and strain rate on the axial instability strain. It is impossible practically to separate the effect on the strain hardening index n of grain size changes from the other metallurgical changes occurring. The measured n-value includes the effect of changes in grain size, see equation (5). In the isothermal case

$$\varepsilon_i = \frac{n}{1 - m\,\frac{d\ell n\dot{\varepsilon}}{d\varepsilon}} \tag{8}$$

In region II of the three region sigmoidal log σ vs log $\dot{\varepsilon}$ plot, m is greater than the corresponding values in regions I and III. Provided that the strain rate increases as the strain increases instability is suppressed or postponed in the superplastic region. Further, an increase in grain size during deformation will always increase the n-value hence stabilizing plastic flow:

$$n = n_1 + a\frac{d\ \ell nL}{d\ \ell n\varepsilon} \tag{9}$$

Numerous researchers have observed grain coarsening during superplastic flow, e.g. Watts and Stowell(8). Any grain coarsening will stabilize plastic flow, if deformation remains in the superplastic domain.

Fracture of Superplastic Materials

The two modes of fracture in superplastics are rupture and fracture in an apparently brittle manner after a reduction in area of less than 100%.

It has been suggested that the mechanism of the latter mode of fracture is the interlinking of cavities which form in many superplastic materials during plastic deformation. Observations confirm that cavities form along the entire gauge length of the specimen and grow with increasing axial strain.

In superplastic materials which fail by rupture it is clear that cavitation is suppressed. Further, the local strain rate within the neck will be appreciably higher than the overall strain rate. The result of this is that the temperature rise in the neck may well be sufficient to cause dynamic recrystallization. Eventually the material within the neck will neck down to 100% reduction in area.

Taplin and Smith(9) have reported that in a cavitating superplastic material there is a resistance to cavity interlinkage. It seems, further, that there is a resistance to the formation of localized shear bands between cavities in region II when the grain size effect is of paramount importance. However, as soon as necking is initiated the local strain rate within the neck will be larger than the prior uniform strain rate. This effect may eventually cause a transition in mode of plastic deformation from region II to the non-superplastic region III. Deformation in region III is known to be relatively insensitive to grain size.

The increase in local temperature in the neck may contribute to a degree of grain coarsening. If an increase in temperature results in grain coarsening there are two competing effects of temperature rise: (a) it will displace superplastic region II to higher strain rates and (b) it will cause grain coarsening which displaces region II to lower strain rates. At first sight these two opposing effects would seem to make the conditions for the onset of instability complicated. However, once the grain size becomes larger than a critical value, the material no longer behaves in a superplastic manner.

The thermo-plastic instability strain is given by(7)

$$\gamma_i = -\frac{n}{\frac{A}{\rho c}\left(\frac{\partial \tau}{\partial T}\right)_{\gamma,\dot{\gamma}}} \tag{10}$$

assuming the strain rate and temperature are constant. However, with the above influence of temperature rise, deformation may eventually move from region II to region III. In region III the effects of grain size are relatively small and it is permissible to assume that $a \to 0$ and therefore $n = n_1$. A conclusion of this is that the activation of a thermo-plastic shear instability requires a change in mode of deformation from region II to region III.

If it is possible that deformation is stabilized in region II and no transition to region III occurs, then it is possible for cavities to interlink by decrease in the net sections between them to zero width. This third possible mode of fracture which precludes the onset of shear instability is the same as McClintock's model for void coalescence(10).

In relation to the total time of a tensile test, the activation of shear instabilities between cavities in superplastic materials and co-commitant fracture will seem to be rapid. Also because the plane of minimum section will be small in diameter and the cavities large (since they will have been growing throughout plastic deformation) it may well be that fracture is the result of the activation of a relatively small number of thermo-plastic shear instabilities.

Conclusions

For a superplastic material which does not cavitate fracture by rupture is expected. On the other hand for superplastics which do cavitate, two modes of fracture are described depending on whether deformation remains in region II or III. If grain coarsening occurs thermo-plastic shear instabilities occur between cavities when there is a transition in mode of deformation from II to III. Alternatively, if deformation is stabilized in region II, shear instability is suppressed and fracture occurs by the growing together of voids according to McClintock's model.

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