Physical Aspects of Superplastic Instability

B. Baudelet and M. Suéry

Institut National Polytechnique de Grenoble
Génie Physique et Mécanique des Matériaux
Unité de Recherche Associée au CNRS No. 793
ENSPG - BP. 46
38402 Saint-Martin d'Hères Cedex, France

CONTENTS

Page

Abstract

This paper details the microstructural changes occurring in superplastic materials that can lead to plastic instability and earlier fracture. Grain size evolution, variation of composition and cavitation are particularly considered and their influence discussed in the light of examples taken from the literature.

1. Introduction

It is generally accepted that the strain-rate sensitivity of the flow stress is of primary importance for the achievement of large elongations in superplastic materials owing to its influence in necking resistance during tensile deformation. The relationship between this parameter and elongation was indeed demonstrated for a broad range of materials /1/. However, large m values are usually not sufficient to guarantee large strains to fracture. The reason for the breakdown in this correlation is mainly microstructural changes that can occur during the course of deformation. These include size evolution of the microstructure, composition variation either in the whole specimen or in preferential regions and cavity or crack generation. These phenomena can influence the plastic stability of the flow or even lead to earlier fracture of the material.

The aim of this paper is to detail these microstructural changes and to analyse their possible influence on flow stability. For this purpose, the material will be considered as superplastic in the initial state with a grain size small enough for accommodated grain boundary sliding to operate. Theoretical considerations on plastic stability will, however, be presented first in order to derive some quantitative predictions.

2. Theoretical Considerations on Plastic Stability

Several criteria of tensile stability have been proposed in the literature based on the general assumption that the load all along the gauge length of the sample is constant. One of the simplest ones is that given by Hart /2/ who ends up with the condition of stable flow in the form:

$$\frac{\gamma + m - 1}{m} \geq 0 \qquad (1)$$

where m and γ are the strain-rate sensitivity and strain sensitivity of the flow stress:

$$m = \left(\frac{\partial Ln\sigma}{\partial Ln\dot{\epsilon}}\right)_{\epsilon,T} \; ; \qquad \gamma = \left(\frac{\partial Ln\sigma}{\partial \epsilon}\right)_{\dot{\epsilon},T}$$

These parameters are purely rheological ones and include possible variations with strain and strain-rate of the flow stress due to microstructural changes. One problem is to define the pertinent factors which are able to adequately characterize the microstructure of a superplastic material.

It is generally admitted that the flow stress only depends on the average grain size with a relationship given as $\sigma \alpha D_p$, where p is a parameter which is normally close to one for superplastic materials.

In general, the influence of the microstructure on the flow stress is given by some function K(S) so that m and γ can be written as:

$$m = m_s + \frac{dLnK(S)}{dLnS}\left(\frac{\partial LnS}{\partial Ln\dot{\epsilon}}\right)_{\epsilon,T} = m_s + m_{\epsilon} \qquad (2)$$

$$\gamma = \gamma_s + \frac{dLnK(S)}{dLnS}\left(\frac{\partial LnS}{\partial \epsilon}\right)_{\dot{\epsilon},T} = \gamma_s + \gamma_{\dot{\epsilon}} \qquad (3)$$

where m_s and γ_s are associated with the physical mechanism which controls deformation. m_{ϵ} and $\gamma_{\dot{\epsilon}}$ appear thus as additional factors which measure the influence of the microstructural evolutions that can take place during deformation. They are assumed to be constant along the gauge length of the sample. Since m_{ϵ} and $\gamma_{\dot{\epsilon}}$ can be either positive or negative, it is obvious that flow stability can evolve during deformation if structural changes take place. It is to be noted, however, that according to Hart's criterion, stable flow is usually not obtained in the absence of structural evolutions under most circumstances since m_s and γ_s are generally close to 0.5 and 0, respectively. These evolutions will now be detailed starting with size variation during deformation.

3. Grain Size Variation

Grain size is usually not fully stable during superplastic deformation and strain enhanced grain growth normally occurs in most materials. Sometimes also dynamic recrystallization takes place leading to some refinement of the structure. Let us examine these two cases separately.

A. Grain Growth

Several quantitative investigations of grain growth have been carried out and various equations were proposed to account for the change in grain size with deformation /3-7/. They are given in Table 1. However, they were derived only over a limited range of strain and strain-rate so that it is quite impossible to obtain general expressions for m_ϵ and $\gamma_{\dot\epsilon}$ due to grain coarsening.

$\gamma_{\dot\epsilon}$ was obtained by Caceres and Wilkinson /5/ who showed that, for the Coronze 638 deformed in the superplastic regime, the stability criterion is satisfied up to 0.75 strain whereas it is not at a larger strain. They, however, did not take into account the effect of grain growth on m given by:

$$m_\epsilon = p \frac{q\, k\, \epsilon\, \dot\epsilon^{\,q}}{D_0 + k\, \epsilon\, \dot\epsilon^{\,q}} \qquad (4)$$

m_ϵ is equal to zero at the beginning of deformation but decreases with strain. This tends to destabilize deformation earlier than without strain enhanced grain growth.

In the case of Zn-Al and Al-Mg-Mn alloys /7/, the situation is a little simpler since parameter β, which measures the rate of grain growth with strain (Table 1), was found to be independent of strain-rate. m_ϵ is thus equal to 0 and $\gamma_{\dot\epsilon}$ to 0.4 and 1.2, respectively, since p was found to be 1.3 and 2. For Al-Mg-Mn, the stability criterion then always satisfied whatever the value of m_s whereas stability depends on this value in the case of Zn-Al. However, in this case, static grain coarsening occurs in addition to strain enhanced grain growth which makes the value of $\gamma_{\dot\epsilon}$ greater than expected at low strain-rate. For example, $\gamma_{\dot\epsilon}$ is close to 1 at a strain-rate of 10^{-5} s^{-1} which is beneficial for plastic stability.

These examples thus show that strain enhanced grain coarsening can have a significant influence on the development of uniform tensile elongation. However, extensive grain coarsening can also lead to a change of the deformation mechanism (m_s decreases) with less plastic stability. This problem was considered by the authors /8/ and they showed that the strain which is possible to achieve under superplastic conditions depends on the deformation path with large elongations if the stress decreases during the test so as to compensate for grain coarsening. Under these circumstances, deformation never takes place with low strain-rate sensitivity values. Experiments were performed in this way on α-β

Table 1

Proposed Laws for Strain-Enhanced Grain Growth

Alloys	Grain Growth Kinetics $D(\mu m)$ $\dot\epsilon\ (s^{-1})$	Values of the Parameters	Reference
Zn-22% Al	$\Delta D/D_o = A \operatorname{Ln} \dot\epsilon + B$	A = -0.087 B 0	/3/
Cu - 42% Zn Cu - 40.6% Zn Cu - 39.4% Zn	$D_\beta \propto (\epsilon/\dot\epsilon)^r$	r = 0.40 r = 0.64 r = 0.55	/4/
Coronze 638	$\Delta D = k\, \dot\epsilon^{\,q}\, \epsilon$	k = 0.2 q = -0.25	/5/
Microduplex steel	$D \propto \epsilon$	α = 0.29	/6/
Zn 22% Al Al-5%Mg-0.6%Mn	$\operatorname{Ln}(D/D_s) = \beta\, \epsilon$	β = 0.3 β = 0.6	/7/

D_o = initial grain size
D_β = grain size of the β-phase
D_s = grain size after static annealing
$\Delta D = D - D_o$

brass /9/, and Fig. 1 shows a plot of elongation versus initial stress; this stress continuously decreases during the test so as to remain always in the superplastic regime. High elongations were thus obtained which would never be obtained under constant stress conditions (Fig. 2).

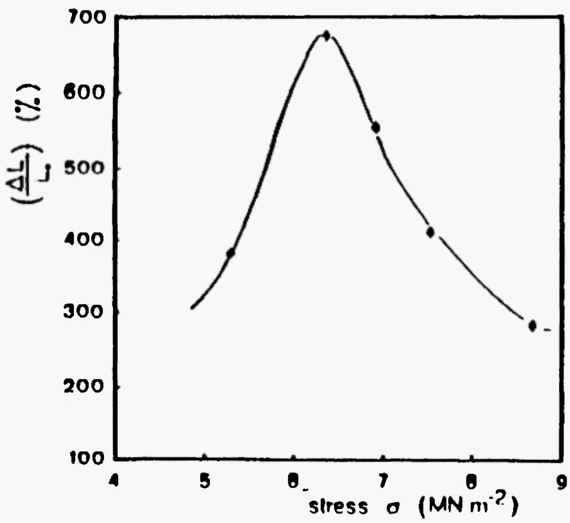

Fig. 1: Tensile elongation as a function of the initial stress at 700 °C in α/β brass. Stress was decreased during the test so that deformation always took place under superplastic conditions /9/.

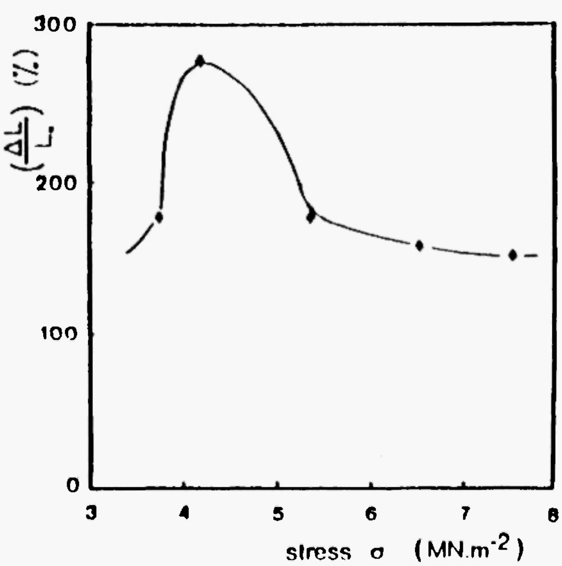

Fig. 2: Tensile elongation as a function of stress at 700 °C in α/β brass. Stress was maintained constant during the test /9/.

B. Recrystallization

Recrystallization can occur during superplastic deformation in materials with grains of various sizes homogeneously distributed in the material. The coarsest grains undergo recrystallization since they are initially deformed under power law creep conditions. Such a phenomenon was observed in Inconel /10/ and one would expect a very favourable effect on plastic stability. However, grain refinement led finally to a bimodal grain-size distribution with a larger proportion of low angle grain-boundaries than in the initial condition. A decrease of the strain-rate sensitivity parameter was then observed with some flow softening and this had a detrimental effect on plastic stability.

4. Compositional Changes

Compositional changes can occur during superplastic deformation for mainly two reasons:

- The composition of the material is not fully stabilized before straining as a consequence of the previous thermomechanical treatment.
- The alloy is tested in an atmosphere which can modify the composition of the outer surface of the sample.

Thermomechanical treatments are usually needed before deformation to generate a very fine grain-size. These are either overaging followed by warm rolling and recrystallization as in the case of 7475 Al or Al-Li alloys or hot extrusion of a two-phase structure in order to break the solidification microstructure.

Overaging of 7475 leads to $MgZn_2$ rich precipitates which cannot be completely dissolved before deformation. The precise influence of this partial dissolution is not fully understood at the moment but it was shown that it is associated with filament formation in the open cavities (Fig. 3) and at the fracture surface with the grain mantle being highly deformed /11/. Simple annealing of the alloy for several hours before straining completely suppresses these filaments, changes the aspect of the grains and decreases cavitation by a factor of 5 to 10. The precipitates or rather their incomplete dissolution seem thus to play a role in the extensive cavitation observed in this type of material.

Loss of elements is another example of compositional change during deformation. This phenomenon was observed essentially in α-β brasses /12/ and Al-Li alloys /13/. Zn-loss leads to the formation of small cavities and sometimes to decohesion at the grain boundaries at the surface of a specimen exposed at high temperature. This can lead to crack formation originating from the periphery of the sample and then to earlier fracture of the material. However, the depth of the Zn-depleted zone is normally limited to a few microns after one or two hours which makes the phenomenon important only at very low strain-rates. Lithium depletion in superplastic Al-Li alloys has been clearly demonstrated by Blandin /13/ and Fig. 4 shows a cross-section of a specimen with a Li-depleted region of about 100 μm at the surface of the sample. This phenomenon occurs as a consequence of the time spent at high temperature but it is also promoted by deformation. The main influence of Li-depletion was found to be enhanced cavitation but it might also produce other effects which can have an influence on plastic stability of the material. Blandin showed in particular that Li-loss can lower self-diffusion coefficients by a factor of about 10 which may have a considerable influence on the superplastic mechanism.

5. Cavitation

Cavitation is a very important phenomenon in superplastic materials since most of them cavitate during deformation. There are two ways to consider cavitation from a stability point of view:

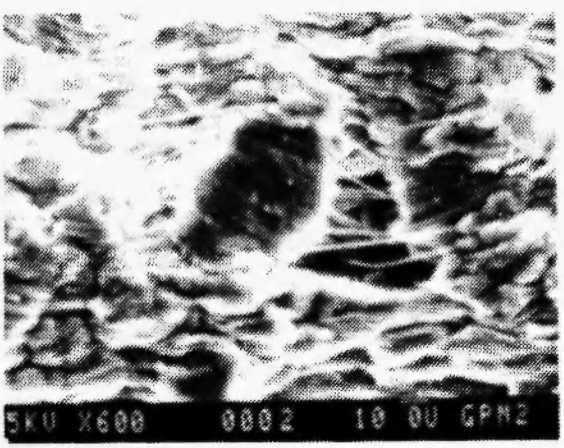

Fig. 3: Filaments observed in an open cavity of a 7475 Al-alloy deformed in the superplastic regime at 516 °C.

Fig. 4: Li-depleted region in an annealed Al-Li alloy displayed by the lack of T_2 (Al_2CuLi) precipitates /13/.

- The cavity volume fraction is considered as a structural parameter which can enter the constitutive equation of the material since it reduces the cross-section of the specimen by a factor related to the cavity volume fraction, C_v. m_ϵ and $\gamma_{\dot{\epsilon}}$ are then negative so that cavity generation enhances the development of instabilities. Moreover, since C_v is usually a sensitive function of ϵ ($C_v = C_{vo} \exp K\epsilon$), necking will enhance cavity development resulting in premature failure by void coalescence.
- The presence of cavities introduces a geometrical defect which will develop faster in a necked region than in the bulk. Numerical calculations of tensile stability were done with K and m as parameters which were assumed to be constant during the whole course of deformation. It was shown that the value of m greatly affects the theoretical strain to failure but its influence is only observed when cavity growth is not very important (K < 2). It becomes almost completely independent of m in the range m > 0.5 if K is greater than ≈ 3 (Fig. 5). For calculation, a uniform initial cavity volume fraction of 10^{-3} was assumed with an initial geometrical defect of 5×10^{-3}. Such a high value of K

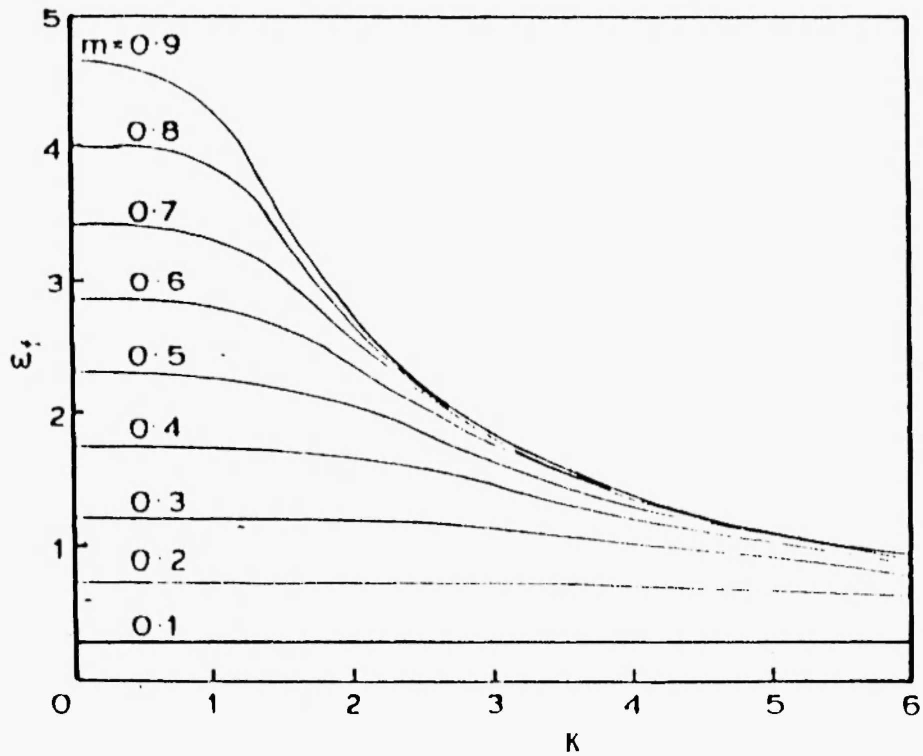

Fig. 5: Calculated fracture strain ϵ_f versus cavity growth rate K for various values of m. The criterion for specimen failure was taken to be either $\epsilon_N/\epsilon - 2$ or $C_{VN} = 0.30$ where ϵ_N and C_{VN} are strain and cavity volume fraction in the neck /14/.

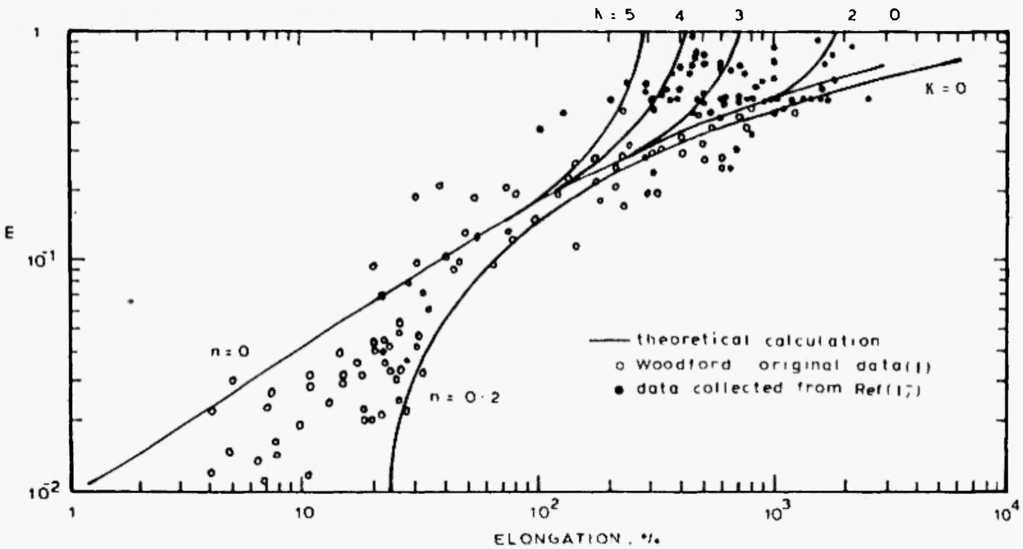

Fig. 6: Relation between elongation to rupture and strain rate sensitivity: comparison between theoretical calculations and experimental results. n is strain hardening coefficient /14/.

is observed in many superplastic alloys (Cu alloys /15/, 7475 /11/ and α-β brasses with large α phase volume fractions /16/ so that cavitation appears as a very important factor which dramatically limits the strain to failure even if the strain-rate sensitivity parameter is very high. Fig. 6 shows comparison between theoretical analysis of the influence of m on elongation to fracture and experimental data. The figure shows that for high values of m most of the experimental data correspond to smaller elongations than those predicted, assuming only the influence of m on plastic stability ($\gamma=n/\epsilon=0$; $K=0$). This result is explained by the destabilizing effect of the cavity growth rate. For low values of m, however, the elongations are greater than predicted owing to the stabilizing effect of strain hardening as is usually observed in conventional plasticity.

6. Conclusion

Several microstructural phenomena can influence plastic stability of superplastic materials; among them are grain size evolution, compositional changes and cavitation. Their effects have been reviewed in this paper and discussed with particular examples taken from the literature. Grain coarsening is found to contribute to the uniformity of deformation. It must be limited, however, to avoid transition to non-superplastic conditions. Cavitation is always detrimental for superplastic stability. It can occur as a result of some compositional effects in the alloys. Therefore, particular attention must be given to the initial state of the material and for some alloys also to the environment.

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