A possible stabilizing effect of work hardening on the tensile performance of superplastic materials

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Introduction

Superplastic deformation:

- Stability in tensile testing

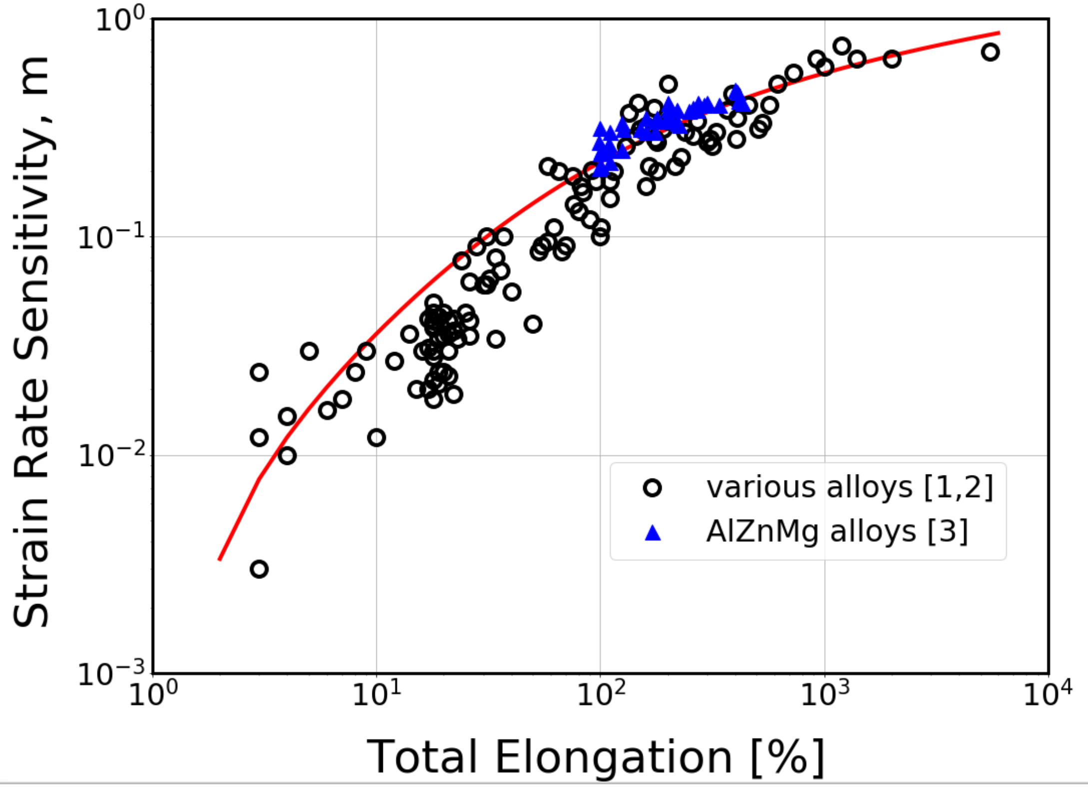
  -> extremely high neck-free elongation

- High values of strain rate sensitivity (SRS): m

Introduction

SRS:

- Unambiguous correlation between ε and *m:*



Introduction

Determination of SRS:

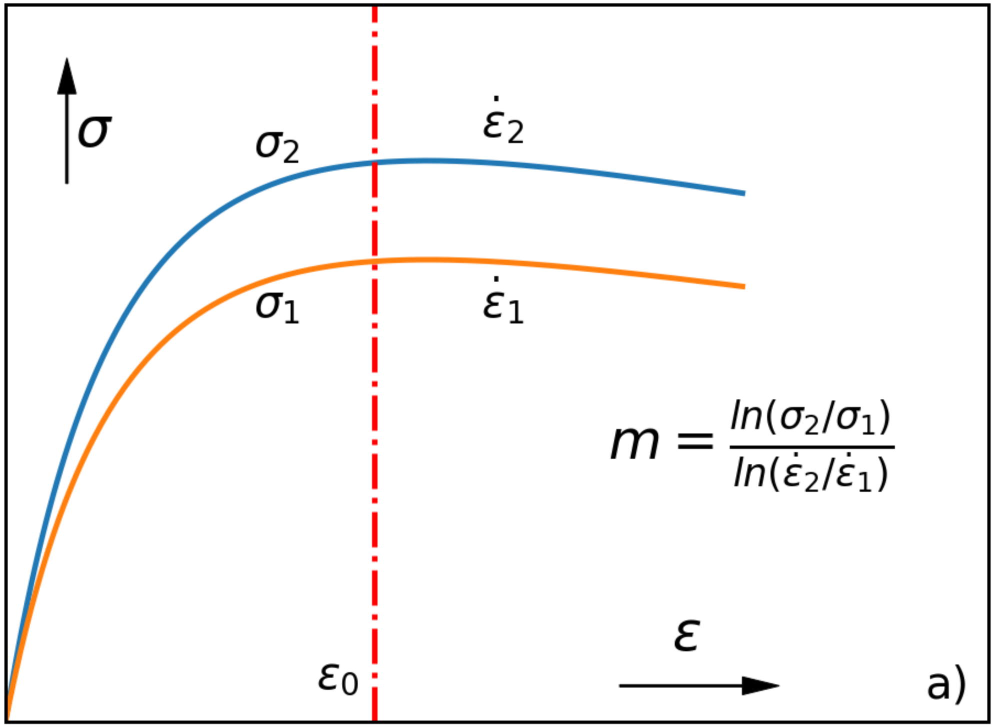
$$\sigma = K\dot{\varepsilon}^{m}$$

$$m = \frac{\partial ln\sigma}{\partial ln\dot{\varepsilon}}$$

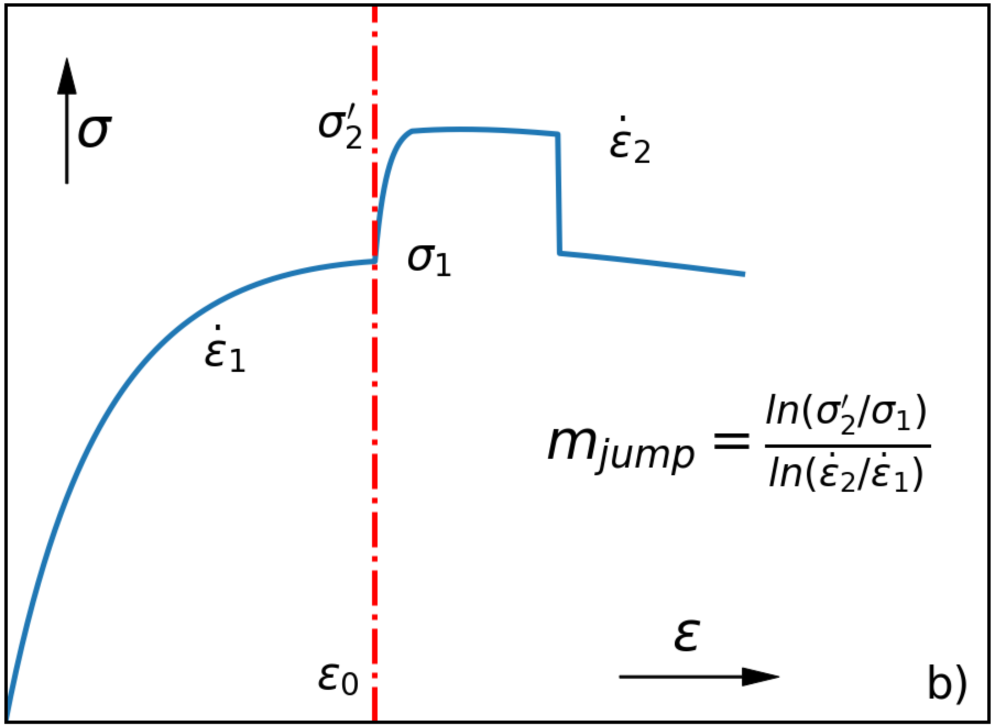
Experiments:

- Tensile testing
- Impression creep
- Depth-sensing indentation testing

Introduction



Introduction



Introduction

- The two SRS values don’t match
- Eg: Al-33Cu alloy:
  - $m_{jump} \sim 0.55 - 0.75$
  - $m \sim 0.3 - 0.7$
- m_{jump} stays constant over a wide range of strain

Stability criteria

Hart-type criterion:

- if ∂A is decreasing in time
- $\frac{\partial ln|\dot{A}|}{\partial lnA} \geq 0$
- smaller cross-section decreases at a slower rate

Fortes-type criterion:

- $\frac{\partial ln|\dot{A}|}{\partial lnA} \geq 1$
- larger cross-section decreases at a faster rate

Fortes > Hart

Stabilizing effect of SRS

higher “*m*” -> higher resistance to neck growth
-> larger max elongation

Let’s define:

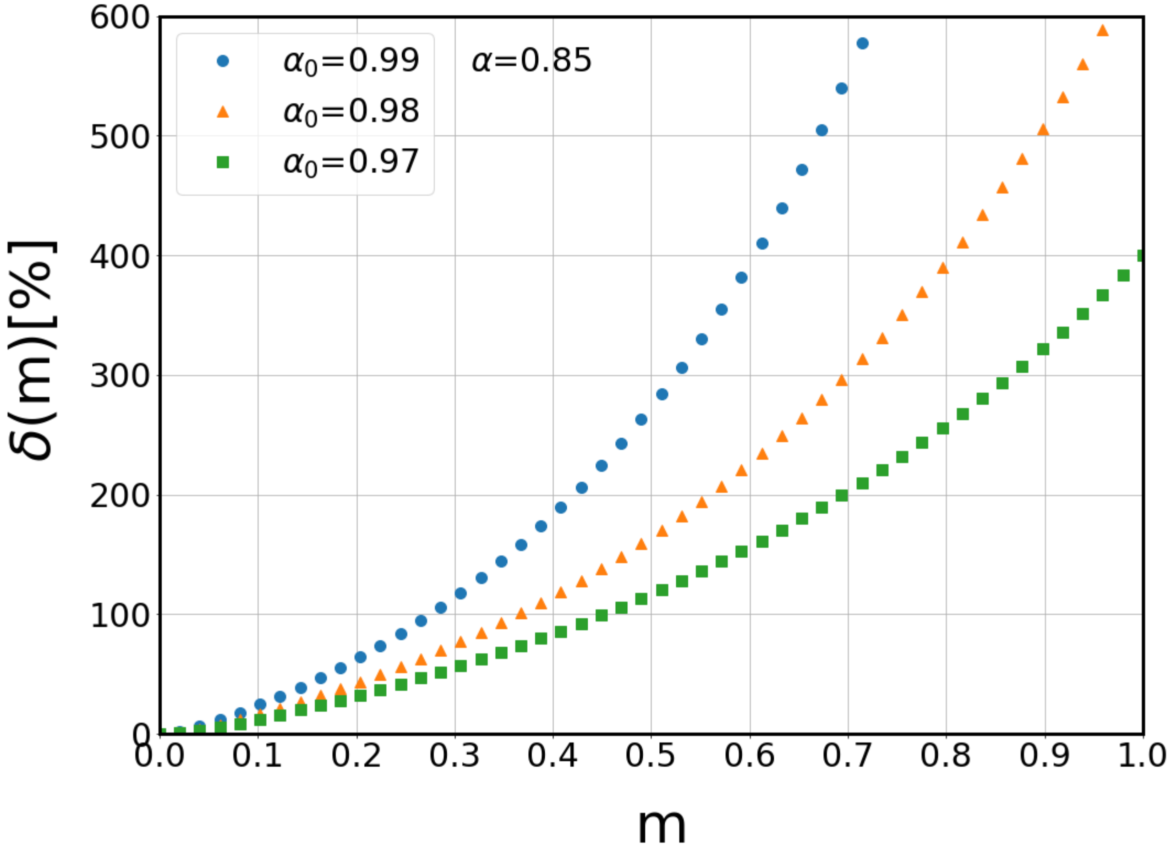
$$F = K \cdot A_2 \cdot \dot{\varepsilon}_2^m = K \cdot A_1 \cdot \dot{\varepsilon}_1^m$$

$$\frac{A_2(t_0)}{A_1(t_1)} = \alpha_0 \text{ and } \frac{A_2(t)}{A_1(t)} = \alpha$$

We get:

$$\delta(m)[\%] = \left\{ \left[\frac{1-\alpha^{1/m}}{1-{\alpha_0}^{1/m}} \right]^m - 1 \right\} \cdot 100$$

Stabilizing effect of SRS



Stabilizing effect of SRS

Considering the stability criteria:

- no work hardening
- superplasticity arises due to general material resistance to neck development
- higher SRS leads to lower neck development rate
- since $\frac{\partial \dot{\varepsilon}}{\partial A} < 0$, Fortes criterion is not working
- $\sigma = K\dot{\varepsilon}^m$ only stands for quasi-stable tensile test

Stabilizing effect of work hardening

Other factors must be considered:

- work hardening
- $\sigma = K \cdot \dot{\varepsilon}^m \cdot \varepsilon^n$

For superplasticity:

- $m \approx 0.5, n \approx 0$
- even if *n* is small, it may yield a stabilizing effect
- since:
  - $\varepsilon = \ln(l/l_0)$ and starts from 0
  - l/l_0 starts from 1, both describe the deformation
  - $l/l_0 = e^{\varepsilon n}$

Stabilizing effect of work hardening

We use:

$$\sigma = K \cdot \dot{\varepsilon}^{m} \cdot e^{\varepsilon n}$$

Lets define:

$$\partial n = n_2 - n_1 = \frac{k}{\varepsilon}$$

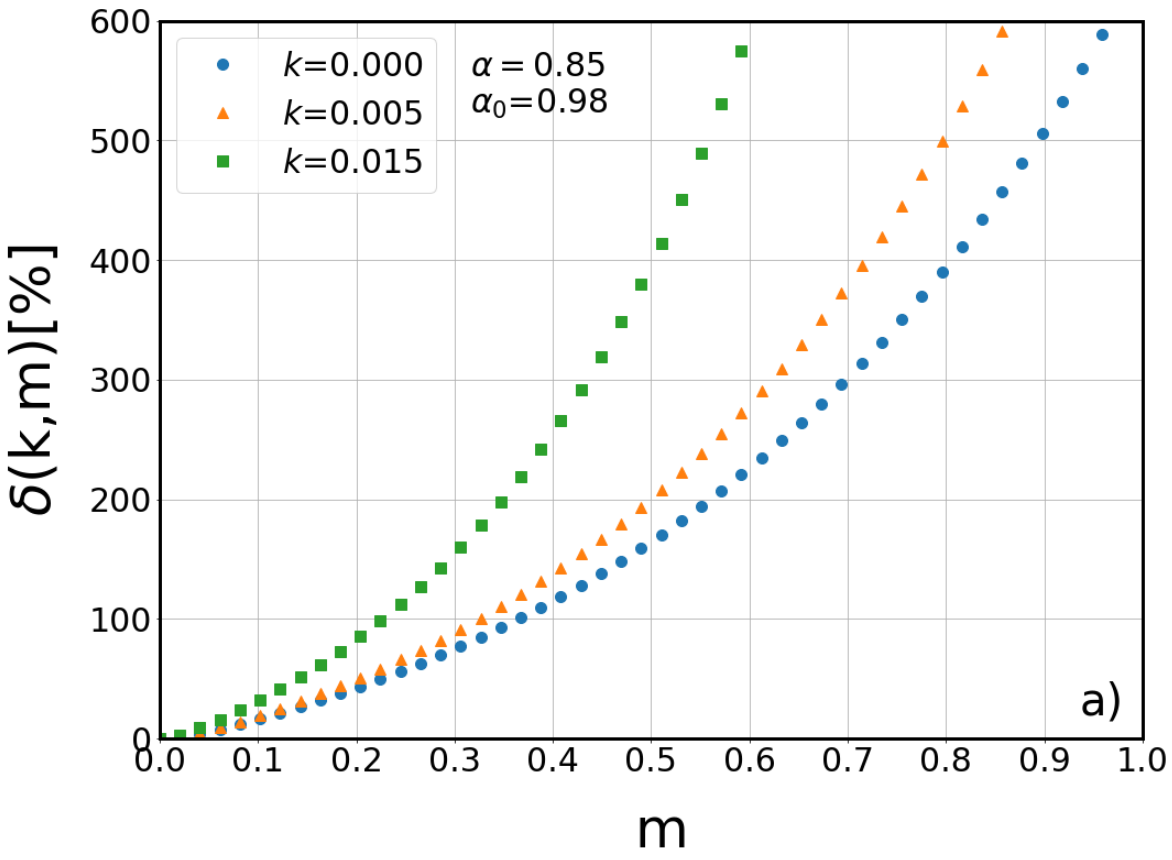
Using the Fortes criterion:

$$k \geq (1 - \alpha_0)(1 - n) \approx (1 - \alpha_0)$$

Defining the percentage elongation:

$$\delta(k, m)[\%] = \left\{ \left[\frac{\alpha^{1/m} - e^{-k/m}}{{\alpha_0}^{1/m} - e^{-k/m}} \right]^{m} - 1 \right\} \cdot 100$$

Stabilizing effect of work hardening



Effect of work hardening on the determination of SRS

Back to the introduction part:

- different values of *m* for different determining methods

If we deform different specimens at different strain rates, at a given strain they may be characterized by the same *n*.

$$\sigma_1 = K \cdot \dot{\varepsilon}_1^m \cdot e^{\varepsilon_0 n}$$
$$\sigma_2 = K \cdot \dot{\varepsilon}_2^m \cdot e^{\varepsilon_0 n}$$
$$m = \frac{\ln(\sigma_2/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}$$

Effect of work hardening on the determination of SRS

If we apply a strain rate change:

- there is a transient period at ε_0
- the work hardening increases from n_1 to n_2
- this leads to an increased stress:

$$\sigma_1 = K \cdot \dot{\varepsilon}_1^m \cdot e^{\varepsilon_0 n_1}$$
$$\sigma_2{}' = K \cdot \dot{\varepsilon}_2^m \cdot e^{\varepsilon_0 n_2}$$

$$m_{jump} = \frac{\ln(\sigma_2{}'/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} = m + \frac{(n_2 - n_1)\varepsilon_0}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}$$

Summary

- Based on stability criteria:
  - higher SRS leads to higher maximum elongation
  - large deformation in superplasticity arises because of the material resistance to neck development, not neck formation
  - so the process for tensile testing is regarded as quasi-stable.

Summary

- To satisfy the criteria for real deformations:
  - new equation which considers SRS and work-hardening rate
  - work hardening increases the maximum elongation in every case
  - if hardened enough, fulfilling the Fortes criterion, necks will cease to develop and will disappear
- The assumption of work hardening effect:
  - possible interpretation of the differences that are often observed experimentally for different determination methods.

Thanks for barely listening!

Acknowledgements

Ref: **Nguyen Q. Chinh, Gergely Rácz, Jenő Gubicza, Ruslan Z. Valiev, Terence G.Langdon**, "*A possible stabilizing effect of work hardening on the tensile performance of superplastic materials*".

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