Materials Science & Engineering A 759 (2019) 448–454

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

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

Nguyen Q. Chinh[a], Gergely Rácz[a], Jenő Gubicza[a], Ruslan Z. Valiev[b,c], Terence G. Langdon[d,*]

[a] Department of Materials Physics, Eötvös Loránd University, H-1117 Budapest, Pázmány Péter Sétány 1/A, Hungary
[b] Institute of Physics of Advanced Materials, Ufa State Aviation Technical University, 12 K. Marx Str., Ufa, 450008, Russia
[c] Laboratory for Mechanics of Bulk Nanostructured Materials, Saint Petersburg State University, 28 Universitetsky pr., Peterhof, Saint Petersburg, 198504, Russia
[d] Materials Research Group, Department of Mechanical Engineering, University of Southampton, Southampton SO17 1BJ, UK

ARTICLE INFO

Keywords:
Stability criterion
Strain rate sensitivity
Superplasticity
Tensile testing
Work hardening

ABSTRACT

In general, the process of superplastic deformation is regarded as steady-state so that the flow stress is given as a function of the strain rate only, thereby emphasizing the significance of the strain rate sensitivity and its determining methods. In this work, in addition to the important role of the strain rate sensitivity, it is shown that it is necessary also to consider the stability criteria for real, stable superplastic deformation through other factors such as work hardening. A possible scenario is proposed to describe the process whereby the work hardening rate may stabilize the deformation process when a perturbation occurs in the cross-section of the sample. The assumption of a work hardening effect is confirmed by its application for interpretation of the systematic deviations observed between the strain rate sensitivities determined experimentally using different experimental methods.

1. Introduction

There are two important characteristics of superplastic deformation. First, superplastic materials exhibit stability in tensile testing, leading to extremely high, neck-free elongations of several hundreds of percent. Second, superplastic materials are characterized by high values for the strain rate sensitivity (SRS). According to many experimental results [1–3], there is an unambiguous correlation between the maximum elongation and the corresponding strain rate sensitivity, m, as shown in Fig. 1. Due to this relationship, many studies have been focused on a determination of the SRS rather than the tensile elongation when the ductility and/or the superplastic behavior of materials is investigated.

In general, a determination of the SRS is conducted by using the stress-strain rate ($\sigma - \dot{\varepsilon}$) relationship which is expressed as

$$\sigma = K\dot{\varepsilon}^m \tag{1}$$

where K is a temperature-dependent material constant. Using eq. (1), the strain rate sensitivity parameter $\left(m = \frac{\partial ln\sigma}{\partial ln\dot{\varepsilon}}\right)$ is the slope of a double-logarithmic plot of $ln\sigma - ln\dot{\varepsilon}$ taken at any selected strain rate. Because of the significance of this parameter, several methods were developed including tensile testing [4–9], impression creep [3,10,11] and depth-sensing indentation testing [12–16] for determinations of the SRS.

Considering the conventional tensile tests, the main methods for a determination of SRS are shown schematically in Fig. 2.

Individual specimens may be deformed by different ($\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$) strain rates (see Fig. 2a) and then the corresponding flow stresses σ_1 and σ_2 obtained at a specific (constant) strain can be used for an estimation of the SRS as

$$m = \frac{ln\sigma_2 - ln\sigma_1}{ln\dot{\varepsilon}_2 - ln\dot{\varepsilon}_1} = \frac{ln(\sigma_2/\sigma_1)}{ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} \tag{2}$$

In practice, alternative and more usual strain rate changes or jumps from $\dot{\varepsilon}_1$ to $\dot{\varepsilon}_2$ are imposed on a single specimen (see Fig. 2b) and the corresponding flow stresses σ_1 and σ_2' are used to determine the so-called m_{jump} SRS which is defined as:

$$m_{jump} = \frac{ln\sigma_2' - ln\sigma_1}{ln\dot{\varepsilon}_2 - ln\dot{\varepsilon}_1} = \frac{ln(\sigma_2'/\sigma_1)}{ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} \tag{3}$$

As a general remark, experimental results [4,5] show that in determinations of the SRS at a given strain the value of m obtained by eq. (2) is not the same as that of m_{jump} obtained by eq. (3). For example, for the Al–33Cu superplastic alloy it was shown that the value of m_{jump} ($\sim$0.55–0.75) was systematically higher than the value of m ($\sim$0.3–0.7) [5]. Furthermore, the value of m_{jump} remained nearly constant over a wide range of strain at a given value for the ratio $\dot{\varepsilon}_2/\dot{\varepsilon}_1$ but the value was dependent upon the specific ratio of $\dot{\varepsilon}_2/\dot{\varepsilon}_1$.

* Corresponding author.
E-mail address: langdon@usc.edu (T.G. Langdon).

https://doi.org/10.1016/j.msea.2019.05.063
Received 9 March 2019; Received in revised form 14 May 2019; Accepted 16 May 2019
Available online 18 May 2019
0921-5093/ © 2019 Published by Elsevier B.V.

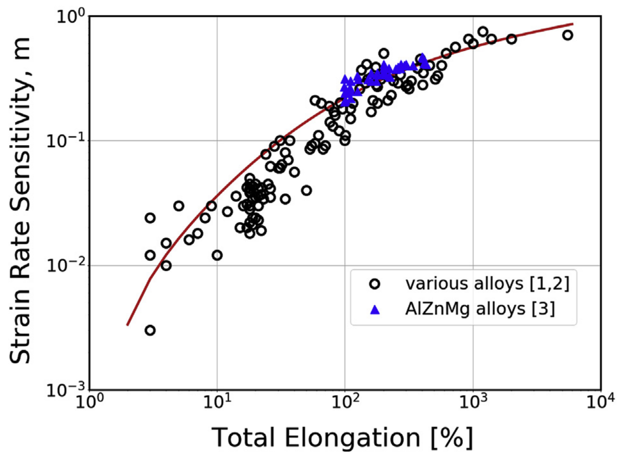

Fig. 1. Relationship between strain rate sensitivity and maximum elongation for several metals [1–3].

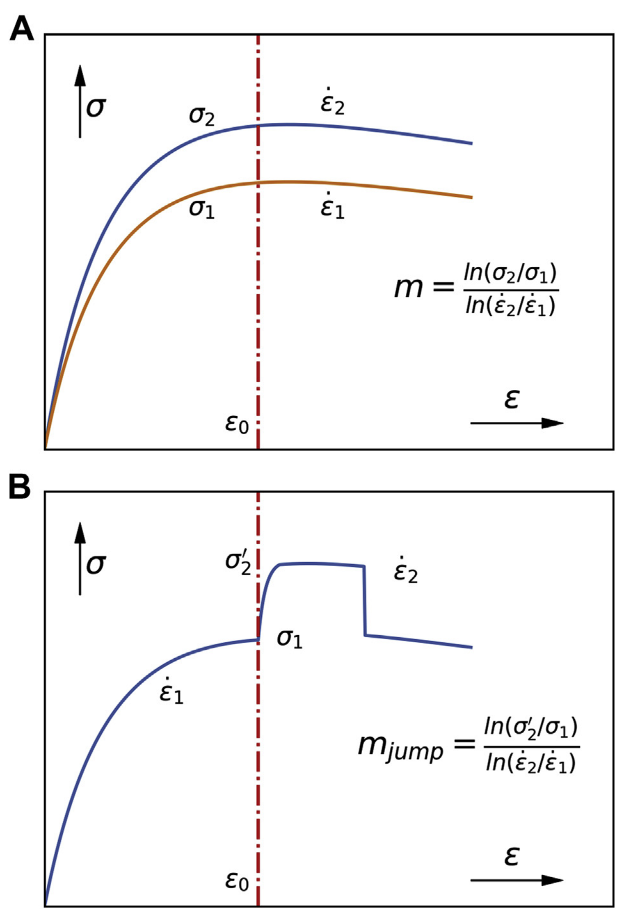

Fig. 2. Main methods for determination of the SRS carried out by: a) different measurements on individual specimens and b) a strain rate jump on a single specimen.

Another general remark is related to the overall stability of the superplastic materials. It is difficult to believe that tensile testing of up to several hundreds of percent, even when occurring with an overall visual homogeneity, does not incur the localized formation of a temporary neck.

The present research was initiated to investigate the stability of tensile deformation in superplastic materials by applying appropriate stability criteria. The role of work hardening is examined as a possible scenario for stabilizing the effect of the superplastic deformation.

2. Stability criteria for plastic deformation during tensile testing

The simplest mode for deformation is the tensile test which is easily described and interpreted. For tensile deformation of a specimen having an instantaneous homogenous gauge length of $l = l(t)$ and a cross-sectional area of $A = A(t)$ at time t, the derivation in time is of the form

$$\dot{l} \geq 0 \ \ and \ \ \dot{A} \leq 0 \tag{4}$$

and, apart from a very small amount of elastic deformation, the volume of the specimen is considered constant. This means that at every time, t, it follows that

$$l{\cdot}A = l_0{\cdot}A_0 = constant \tag{5}$$

from which

$$l{\cdot}\dot{A} + \dot{l}{\cdot}A = 0.$$

Furthermore, during tensile testing, from the definition of strain, $\varepsilon = \ln(l/l_0)$, the strain rate, $\dot{\varepsilon}$, of the sample is given as

$$\dot{\varepsilon} = \frac{\dot{l}}{l} = -\frac{\dot{A}}{A} \tag{6}$$

It is necessary to now consider the most frequent stability criteria on the bases of the change of the cross-section of the specimen.

2.1. Hart-type criterion

According to the Hart-type criterion [17], the deformation may be regarded as a stable process if the possible local deviation of the cross-section, ∂A, is decreasing in time. Physically, this means that a smaller cross-section will decrease at a slower rate. Therefore, the Hart-type criterion is mathematically expressed as

$$\frac{\partial \dot{A}}{\partial A} \leq 0 \tag{7}$$

Since $A/\dot{A} < 0$, the inequality in eq. (7) can be treated in the following form:

$$\frac{\partial ln|\dot{A}|}{\partial lnA} \geq 0 \tag{8}$$

It should be noted that in practice eq. (7) does not provide a satisfactory and explicit criterion for the overall stability because it may be fulfilled even if the ratio of the diameters of the neck and the other parts of the sample remain unchanged.

2.2. Fortes-type criterion

Concerning the Fortes-type stability criterion [18], the deformation process is stable if the larger cross-sectional area decreases at a faster rate so that the following relationship is valid:

$$\frac{\partial ln|\dot{A}|}{\partial lnA} \geq 1 \tag{9}$$

Taking into account the relationship given in eq. (6) between strain rate, $\dot{\varepsilon}$, and the change rate, $\dot{A}$, of the cross-section, the criterion in eq. (9) can be equivalently described in the following form:

$$\frac{\partial \dot{\varepsilon}}{\partial A} \geq 0 \tag{10}$$

where this means that the strain rate is faster for a larger cross-section so that the ratio of the neighboring cross-sections tends to one. Comparing eqs. (8) and (9), it is necessary to emphasize that mathematically the Fortes-type criterion is stronger than the Hart-type criterion. Physically, the Fortes-type condition includes not only the Hart-type criterion in the case of a local deviation in the cross-section but it also prescribes a ceasing of such deviation. This means that if a neck occurs in the sample then both conditions require a lower changing-rate of the cross-section of the neck (as in eq. (8)) and, according to the stronger

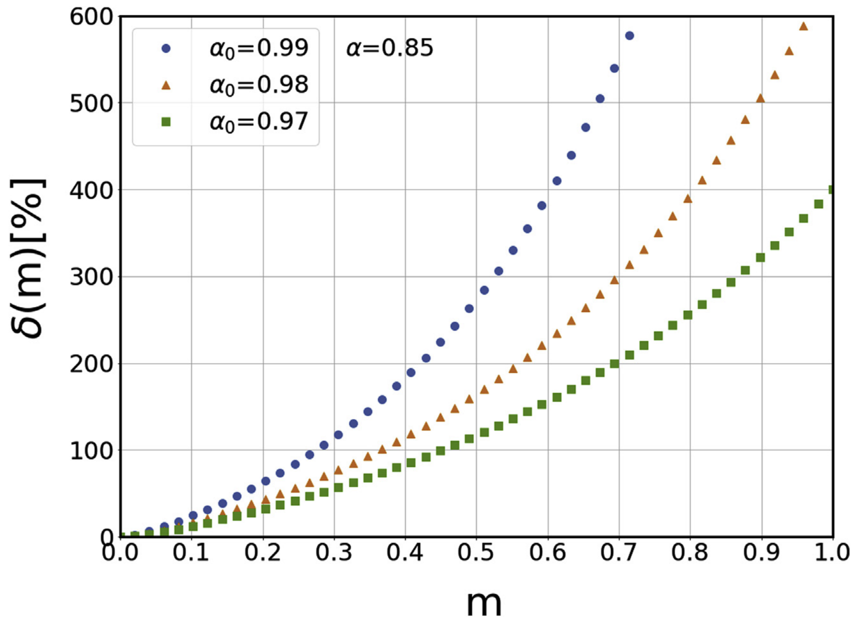

Fig. 3. The expected maximum elongation, δ(m), as a function ofthe SRS for different values of α_0 (see eq. (13)).

Fortes-type condition in eq. (9), the neck should disappear during further deformation. This condition is equivalent to the lower strain rate occurring in the neck relative to that of the remaining normal or uniform part of the sample (see eq. (10)).

3. The stabilizing effect of the SRS in quasi-stable tensile deformation

As already noted, the relationship between the SRS and the maximum tensile elongation is well documented both experimentally [1–3] and theoretically [19]. Taking into account the relevant stability criteria, it is first necessary to investigate the effect of the SRS on the general stability of superplastic deformation.

It is assumed that a plastic instability occurs as neck formation in the specimen. It is well established that higher values of m relate to a more effective resistance to neck growth [19]. For example, using eq. (1) for $m = 1$ for the case of Newtonian viscous flow, as the force, F, is constant at any cross-sectional position along the longitudinal axis of the sample, it is possible to write:

$$\sigma{\cdot}A = K{\cdot}\dot{\varepsilon}{\cdot}A = F = const. \tag{11}$$

Thus, substituting the value of $\dot{\varepsilon}$ by $-\dot{A}/A$ from eq. (6) leads to

$$K{\cdot}\frac{\dot{A}}{A}{\cdot}A = const.\ ,$$

from which

$$\dot{A} = const. \tag{12}$$

at any cross-sectional point along the sample. This means that even if a neck is present it will not propagate.

In general, using eq. (1) it can be shown that the higher the value of the SRS so the larger the maximum elongation [19]. Assuming that a neck with a cross-section of A_2 occurs at time t_0 on a specimen having a cross-section of A_1, and assuming that the neck propagates, so the time interval (t_0, t) is given by the following conditions:

$$\frac{A_2(t_0)}{A_1(t_0)} = \alpha_0 \ \text{and}\ \frac{A_2(t)}{A_1(t)} = \alpha \tag{13}$$

It is now possible examine the effect of m on the maximum elongation that may be reached within this time interval. Thus, denoting the strain rates of the neck and the remaining part of the sample as $\dot{\varepsilon}_2$ and $\dot{\varepsilon}_1$, respectively, the constant force, F, along the sample leads through eq. (1) to:

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

from which, using eq. (6), there is the following relationship:

$$A_2{}^{1/m}{\cdot}\frac{\dot{A}_2}{A_2} = A_1{}^{1/m}{\cdot}\frac{\dot{A}_1}{A_1}$$

or in the differential form it may be expressed as

$$A_2^{1/m}{\cdot}\frac{dA_2}{A_2} = A_1{}^{1/m}{\cdot}\frac{dA_1}{A_1} \tag{14}$$

Integrating both sides of eq. (14) over the time interval, (t_0, t) leads to:

$$\int_{A_2(t_0)}^{A_2(t)} A_2^{\frac{1}{m}-1}dA_2 = \int_{A_1(t_0)}^{A_1(t)} A_1^{\frac{1}{m}-1}dA_1 \tag{15}$$

Then using the ratios given in eq. (13), eq. (15) gives

$$A_1(t) = \left[\frac{1-\alpha_0^{1/m}}{1-\alpha^{1/m}}\right]^m{\cdot}A_1(t_0)$$

It is noted that this latter relationship is valid if the deformation in the neck is negligible. The relationship then permits a calculation of the percentage elongation, $\delta(m)$, of the sample as a function of the SRS in the time interval (t_0, t). Beside a small, diffuse neck, $\delta(m)$ may be expressed approximately in the following form:

$$\delta(m)[\%] = \left\{\left[\frac{1-\alpha^{1/m}}{1-\alpha_0^{1/m}}\right]^m - 1\right\}{\cdot}100 \tag{16}$$

Fig. 3 shows the effect of m on the value of $\delta(m)$ predicted by eq. (16) for a final 15% variation in cross-section ($\alpha = 0.85$) at different initial conditions as represented by the individual α_0 values. It is readily apparent that in all cases the maximum elongation depends strongly on the value of the SRS. The value of $\delta(m)$ increases with increasing m and this is consistent with the extensive experimental data shown in Fig. 1. The same phenomenon of neck formation and the effect of SRS on the development of the neck was examined earlier in a detailed experimental investigation using the superplastic Zn–22Al eutectoid alloy [20].

Considering the stability criteria, it is concluded that based on eq.

(1), without the effect of work hardening, the superplasticity arises because of the general material resistance to the development of the neck but not to the neck formation *per se*. Thus, the higher the SRS so the lower the rate at which the neck develops. Furthermore, at any time along the sample there is a valid condition given by

$$\frac{\partial\dot{\varepsilon}}{\partial A} < 0$$

so that the Fortes-type stability criterion is not working in this case where a neck is formed and then exists through the whole deformation. This means, therefore, that the conventional eq. (1) represents in practice only a quasi-stable criterion for tensile tests.

4. The stabilizing effect of work hardening

For real, stable superplastic deformation, where the Fortes criterion should be satisfied, other factors characterizing the process of deformation must also be considered. This means that, in addition to the SRS, the effect of work hardening is another important factor in the analysis. In general, the flow stress at a given strain, ε, for any material depends on both the strain rate and the work hardening rate, n, through the relationship [19,21]:

$$\sigma = K\cdot\dot{\varepsilon}^m\cdot\varepsilon^n \tag{17}$$

For room temperature deformation with considerable work hardening, the Hart stability criterion may also be written as

$$\frac{d\sigma}{d\varepsilon} \geq \sigma(1-m). \tag{18}$$

Thus, substituting eq. (17) into eq. (18), the following criterion is obtained for the strain of homogeneous stable deformation:

$$\varepsilon \leq \frac{n}{1-m} \tag{19}$$

Equation (19) shows that for higher values of m and n the necking occurs at higher strains. In effect, therefore, the work hardening stabilizes the homogenous deformation.

For superplastic deformation where $m \approx 0.5$, the value of n is negligible so that $n \approx 0$ and this leads to the general use of eq. (1). However, it will be shown that, even if n is small, its change during superplastic deformation may yield a stabilization effect against necking. In this model, the stabilizing effect of the work hardening appears in the form of an increase in the flow stress which contrasts with that characterizing the steady-state condition as described by eq. (1). It can be seen that using eq. (17) this condition may not be satisfied in every case. For example, at strains of $\varepsilon < 1$ the effect of work hardening, as given by $n > 0$, will cause a decrease in stress relative to the stationary value. In order to avoid such problems in the analysis, it is clear that another relationship other than eq. (17) should be used to take into account the effect of work hardening. Considering the deformation process of a sample by tensile testing, both the dimensionless quantities of ε and l/l_0 equally characterize the amount of deformation, where l_0 is the initial and l is the momentary length of the sample. However, from the viewpoint of this analysis, there is a significant difference between these quantities because while $\varepsilon = ln(l/l_0)$ starts from 0 the value of l/l_0 goes from 1. This means that it is reasonable to use the quantity l/l_0 instead of ε in eq. (17) to take into account the effect of work hardening so that

$$\sigma = K\cdot\dot{\varepsilon}^m\cdot(l/l_0)^n \tag{20}$$

From the definition of ε, the ratio l/l_0 may be expressed as $l/l_0 = e^{\varepsilon}$, so that eq. (20) takes the following form:

$$\sigma = K\cdot\dot{\varepsilon}^m\cdot e^{\varepsilon n} \tag{21}$$

Applying eq. (21) for an investigation of the Fortes criterion given by eq. (10), starting from the condition of $F = \sigma\cdot A = \text{constant}$ along the sample, at any given moment there is

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

from which

$$A\cdot\dot{\varepsilon}^m\cdot e^{\varepsilon n} = \frac{F}{K}$$

Taking the logarithmic form of both sides leads to

$$lnA + m\cdot ln\dot{\varepsilon} + n\cdot\varepsilon = ln\left(\frac{F}{K}\right) = \text{constant}$$

or the following differential form:

$$\partial lnA + m\cdot\partial ln\dot{\varepsilon} + n\cdot\partial\varepsilon + \varepsilon\cdot\partial n = 0 \tag{22}$$

Equation (22) expresses the case where the deformation is not homogenous. Different cross-sections, A, are forming not only by different rates, $\dot{\varepsilon}$, but also with different work hardening rates, n. Thus, using the usual transformations:

$$\partial lnA = \frac{\partial A}{A},\quad \partial ln\dot{\varepsilon} = \frac{\partial\dot{\varepsilon}}{\dot{\varepsilon}}$$

and

$$\partial\varepsilon = \partial ln\left(\frac{l}{l_0}\right) = \partial\ln\left(\frac{A_0}{A}\right) = -\frac{\partial A}{A}$$

eq. (22) may be rewritten as:

$$m\cdot\frac{\partial\dot{\varepsilon}}{\dot{\varepsilon}} = -\frac{\partial A}{A} - \varepsilon\cdot\partial n + n\cdot\frac{\partial A}{A}$$

from which the following differential form is derived:

$$\frac{\partial\dot{\varepsilon}}{\partial A} = -\frac{\dot{\varepsilon}}{m}\cdot\left(\frac{1-n}{A} + \varepsilon\cdot\frac{\partial n}{\partial A}\right) \tag{23}$$

Basing on this relationship, the Fortes-type criterion in eq. (10) is given as:

$$\frac{1-n}{A} + \varepsilon\cdot\frac{\partial n}{\partial A} \leq 0$$

or

$$\frac{\partial n}{\partial A} \leq -\frac{1-n}{A\varepsilon} \tag{24}$$

This represents in practice a complicated gradient effect of inhomogeneous deformation, as the gradient in deformation will result also in a gradient in the work hardening rate.

In order to demonstrate the stabilizing effect of work hardening, it is necessary to investigate a simple case for the interpretation of the Fortes-type criterion given by eq. (24).

Consider again the problem discussed in section 3. Assume that a neck with cross-section of A_2 occurs at t_0 on a specimen having a cross-section of A_1 and suppose also that the neck propagation within the time interval (t_0, t) may be described by eq. (13). Furthermore, assume that the work hardening of the regions having cross sections A_2 and A_1 are characterized by the work hardening rates of n_2 and n_1, respectively. In order to simplify the analysis, assume that

$$\partial n = n_2 - n_1 = \frac{k}{\varepsilon} \tag{25}$$

where k is a constant having a value of $k \geq 0$. This assumption is realistic in practice because, following the initial transient period, n_2 is expected to approximate to n_1 if ε is sufficiently large.

Using the ratio $A_1/A_2 = \alpha_0$ at the moment, t_0, of necking, as in eq. (13), leads to

$$\partial A = A_2 - A_1 = A_1\cdot(\alpha_0 - 1) \tag{26}$$

Substituting eqs. (25) and (26) into eq. (24), and assuming n is small, leads to

$$k \geq (1-\alpha_0)(1-n) \approx (1-\alpha_0) \tag{27}$$

which is the main point of the stabilizing effect of work hardening. The relationship given by eq. (27) means that, if the neck is sufficiently hardened and fulfills the Fortes-type criterion, it will gradually disappear.

It is also interesting to examine the situation where the hardening of the neck is not sufficiently large so that ($k < 1 - \alpha_0$) and the Fortes-type criterion in eq. (10) is not valid. It is now possible to examine the ways in which the work hardening parameter, k, in eq. (25) influences the total elongation.

Using eq. (25) and the constancy of the force along the sample:

$$K \cdot A_1 \cdot \dot{\varepsilon}_1{}^m \cdot e^{n_1 \varepsilon} = K \cdot A_2 \dot{\varepsilon}_2{}^m \cdot e^{n_2 \varepsilon}$$

so that it may be derived that

$$A_1(t) = \left[\frac{\alpha_0{}^{1/m} - e^{-k/m}}{\alpha^{1/m} - e^{-k/m}}\right]^m \cdot A_1(t_0)$$

leading to the percentage elongation, $\delta(k, m)$, of the sample in the time interval, (t_0, t), is given by

$$\delta(k, m)[\%] = \left\{\left[\frac{\alpha^{1/m} - e^{-k/m}}{\alpha_0^{1/m} - e^{-k/m}}\right]^m - 1\right\} \cdot 100 \quad (28)$$

It is noted that for the case of $k = 0$, where there is no gradient in the work hardening rate, eq. (28) leads back to eq. (16) containing only the effect of the SRS.

Fig. 4a shows the maximum elongation predicted by eq. (28) in the function of the strain rate sensitivity, m, at different values of k for the situation where $\alpha_0 = 0.98$ and $\alpha = 0.85$. In all cases, $k < 1 - \alpha_0$ in the Fortes type stability and the neck continuously develops. However, it is apparent that a small amount of neck hardening effectively decreases the rate of neck development and increases the total elongation for the same condition of α_0 and α at any given value of m.

Fig. 4b shows the value of $\delta(k, m)$ as a function of k, indicating the effect of neck hardening for the same values of $\alpha_0 = 0.98$, $\alpha = 0.85$ and $m = 0.5$. It can be seen clearly that the higher the value of k so the larger elongation that is expected. Without the effect of any work hardening so that ($k = 0$) there is a maximum elongation of 160%, whereas a small amount of neck hardening characterized by $k = 0.015$ increases this maximum value to 400%.

5. Effect of work hardening on the determination of the SRS

As noted in the Introduction, the value, m_{jump}, of the SRS determined by using the conventional strain rate change method on one specimen, as in eq. (3) and Fig. 2, is generally higher than the value of m measured from a series of tests carried out on individual specimens at different strain rates (eq. (2)). Considering the effect of work hardening discussed in the preceding section, the difference between m_{jump} and m may be readily interpreted.

For the case of deforming different specimens at different strain rates, it may be assumed that within a narrow range of strain rate the work hardening will depend only on the deformation. Therefore, the stresses σ_1 and σ_2 of the samples deformed by different strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, respectively, at a given strain of ε_0 may be characterized by the same value of n, that is

$$\sigma_1 = K \cdot \dot{\varepsilon}_1{}^m \cdot e^{\varepsilon_0 n}$$

and

$$\sigma_2 = K \cdot \dot{\varepsilon}_2{}^m \cdot e^{\varepsilon_0 n}$$

which together lead to an SRS that is free of a hardening effect so that $m = \frac{ln(\sigma_2/\sigma_1)}{ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}$.

When applying the strain rate change method, and similar to the situation where a neck occurs, because of the transient phenomenon caused by the strain rate change when the strain rate jumps from $\dot{\varepsilon}_1$ to $\dot{\varepsilon}_2$ at a strain of ε_0, the work hardening, n, in eq. (21) increases from n_1 to n_2 where ($n_2 > n_1$). This leads to an increase in stress from

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

to

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

This gives an SRS of the form

$$m_{jump} = \frac{ln(\sigma_2^{\cdot}/\sigma_1^{\cdot})}{ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} = m + \frac{(n_2 - n_1)\varepsilon_0}{ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)} \quad (29)$$

and this is higher than the subscript-free value ($m_{jump} \geq m$) as $\dot{\varepsilon}_2 > \dot{\varepsilon}_1$, $ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1) > 0$ and $n_2 - n_1 \geq 0$. Furthermore, on the basis of eq. (29) it is also clear that the value of m_{jump} may depend on the ratio of $\dot{\varepsilon}_2/\dot{\varepsilon}_1$ as it was observed experimentally [5].

In the present analysis, a possible effect of work hardening is suggested. Nevertheless, it should be emphasized that in general the global superplastic flow may show real strain hardening ($\partial\sigma/\partial\varepsilon > 0$) [6,21,22] or it may be accompanied by strain softening ($\partial\sigma/\partial\varepsilon < 0$) [22–24]. In the latter case, it is well established that the effect of dynamic recovery and/or dynamic recrystallization is stronger than the effect of dislocation multiplication. The present analysis demonstrates that if a neck is formed, but with a higher work hardening relative to the work hardening of the remaining part even at the microscopic level, it may no longer develop but instead may disappear. This leads to the possible stabilizing effect of work hardening. As a theoretical analysis, there are numerous assumptions in the present analysis but nevertheless the overall trends and the resultant conclusions are based firmly on, and are consistent with, the available experimental evidence.

4. Summary and conclusions

1) On the basis of the stability criterions, it is shown that, when taking only the effect of the SRS into account, so a higher the strain rate sensitivity gives a higher maximum elongation. Nevertheless, the large deformation in superplasticity arises because of the material resistance to neck development and not to a lack of neck formation. Thus, the deformation process for tensile testing is regarded as quasi-stable.

2) In order to satisfy the stability criterions for real, stable superplastic deformation, other factors characterizing the deformation process must be considered. A scenario is suggested based on the stabilizing effect of work hardening in tensile testing using a new constitute equation containing both the SRS and the work hardening rate. It is shown that in every case the higher rate of neck hardening improves the maximum elongation expected for any given SRS. Furthermore, if the occurring neck is sufficiently hardened, fulfilling the Fortes-type criterion, it will cease to develop and instead it will disappear.

3) The assumption of a work hardening effect, as well as the use of a new constitutive relationship, is confirmed by possible applications in the interpretation of the differences that are often observed experimentally when the values of the SRS are determined using different experimental methods.

Data availability statement

The data in Fig. 1 were gathered from References 1–3. Other data that support the findings of this study are the results from the work of the authors and they are not available elsewhere.

Conflicts of interest

The authors declare that they have no conflict of interest.

Acknowledgements

This research was supported by the Hungarian-Russian bilateral Research program (TÉT) No. 2017-2.3.4-TÉT-RU-2017-00005 (NQC,

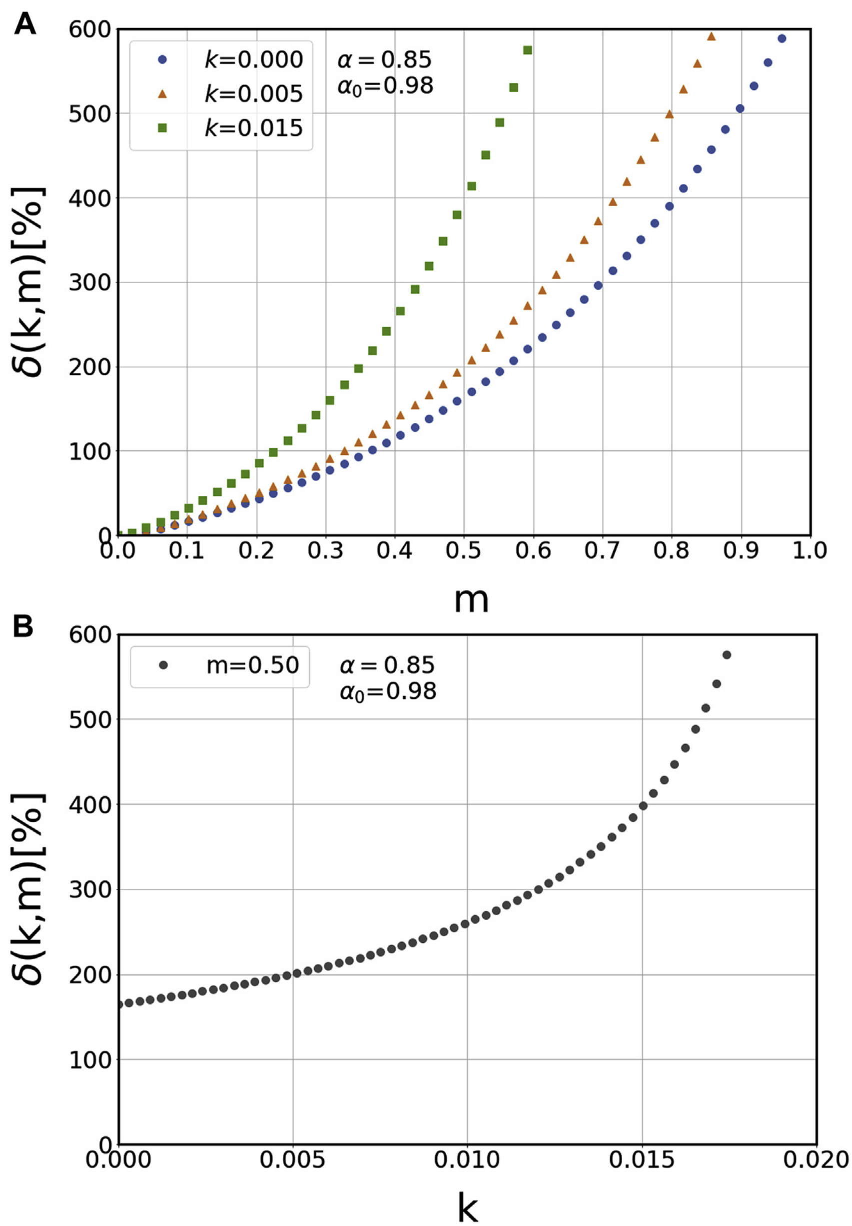

Fig. 4. The expected maximum elongation, δ(k, m) as a function of (a) m and (b) k parameters.

JG). The work was financed partly by the Ministry of Human Capacities of Hungary within the ELTE University Excellence program (1783-3/2018/FEKUTSRAT) and by the Ministry of Science and Higher Education of the Russian Federation under grant agreement No. 14.586.21.0061 (unique project identifier RFMEFI58618X0061) (RZV).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.msea.2019.05.063.

References

[1] D.A. Woodford, Strain-rate sensitivity as a measure of ductility, Trans. ASM 62 (1969) 291–293.
[2] T.G. Langdon, The mechanical properties of superplastic materials, Metall. Trans 13A (1982) 689–701.
[3] N.Q. Chinh, J. Illy, A. Juhász, J. Lendvai, Mechanical properties and superplasticity of AlZnMg alloys, phys. stat. sol. (a) 149 (1995) 583–599.
[4] Y. Song, S. Lian, Mechanical theory of strain rate sensitivity index *m* and new method of measurement using constant load, Mater. Sci. Technol. 5 (1989) 443–449.
[5] T. Hatayama, T. Okabe, H. Takei, Dependence of *m*-value on strain rate in superplastic Al-Cu alloys, Trans. Japan Inst. Metals 27 (1986) 576–583.
[6] H.E. Adabbo, G. González-Doncel, O.A. Ruano, Strain hardening during superplastic deformation of Al-7475 alloy, J. Mater. Res. 4 (1989) 587–594.
[7] Y.M. Wang, E. Ma, Three strategies to achieve uniform tensile deformation in nanostructured metal, Acta Mater. 52 (2004) 1699–1709.
[8] F. Kabirian, A.S. Khan, A. Pandey, Negative to positive strain rate sensitivity in 5xxx series aluminum alloys: experiment and constitutive modeling, Int. J. Plast. 55 (2014) 232–246.
[9] E. Alabort, D. Putman, R.C. Reed, Superplasticity in Ti-6Al-4V: characterisation, modelling and applications, Acta Mater. 95 (2015) 428–442.
[10] N.Q. Chinh, P. Tasnádi, A. Juhász, I. Kovács, Evaluation of the true activation enthalpy of superplastic flow including a threshold stress, J. Mater. Sci. 29 (1994) 2341–2344.
[11] J.C.M. Li, Impression creep and other localized tests, Mater. Sci. Eng. A 322 (2002) 23–42.
[12] I.-C. Choi, Y.-J. Kim, B. Ahn, M. Kawasaki, T.G. Langdon, J.-i. Jang, Evolution of plasticity, strain rate sensitivity and the underlying deformation mechanism in Zn-22%Al during high-pressure torsion, Scripta Mater. 75 (2014) 102–105.
[13] Z.H. Cao, L. Wang, K. Hu, Y.L. Huang, X.K. Meng, Microstructural evolution and its influence on creep and stress relaxation in nanocrystalline Ni, Acta Mater. 60 (2012) 6742–6754.
[14] N.Q. Chinh, P. Szommer, Mathematical description of indentation creep and its application for the determination of strain rate sensitivity, Mater. Sci. Eng. A 611

(2014) 333–336.
[15] M. Kawasaki, J.-i. Jang, Review: micro-mechanical response of an Al-Mg hybrid system synthesized by high-pressure torsion, Materials 10 (6) (2017) 596–610.
[16] V. Maier-Kiener, K. Durst, Advanced nanoindentation testing for study strain rate sensitivity and activation volume, JOM 69 (2017) 2246–2255.
[17] E.W. Hart, Theory of the tensile test, Acta Metall. 15 (1967) 351–355.
[18] M.A. Fortes, The stability of plastic deformation in tension, Int. J. Mech. Sci. 19 (1977) 483–489.
[19] J.W. Edington, K.N. Melton, C.P. Cutler, Superplasticity, Prog. Mater. Sci 21 (1976) 61–158.
[20] F.A. Mohamed, T.G. Langdon, Flow localization and neck formation in a superplastic metal, Acta Metall. 29 (1981) 911–920.
[21] X. Wang, Q. Li, R. Wu, X. Zhang, L. Ma, A review on superplastic formation behavior of Al alloys, Advances in Mater. Sci. Eng. (2018) 1–17. Article ID 7606140.
[22] L. Zhao, T. Yasmeen, P. Gao, S. Wei, Z. Bai, J. Jiang, J. Lin, Mechanism-based constitutive equations for superplastic forming of TA15 with equiaxed finr grain structure, Procedia Eng 207 (2017) 1874–1879.
[23] E. Alabort, D. Putman, R.C. Reed, Superplasticity in Ti-6Al-4V: characterisation, modelling and applications, Acta Mater. 95 (2015) 428–442.
[24] H. Watanabe, K. Ohori, Y. Takeuchi, Superplastic behavior of Al-Mg-Cu alloys, Transaction ISIJ 27 (1987) 730–733.