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Evaluation of the true activation enthalpy of superplastic flow including a threshold stress

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A new method is suggested for the evaluation of the true activation enthalpy for alloys where the strain rate of the superplastic flow varies with a power of an effective stress $\sigma_e = \sigma - \sigma_0$, where σ and σ_0 are the applied stress and a threshold stress, respectively. Some earlier results concerning superplastic AlMgZnCu alloys containing chromium and in which a strongly temperature-dependent threshold stress can be revealed, are reanalysed. The results are in good agreement with the previous ones. It has been shown further that for the alloys investigated the true activation energy increases with increasing chromium content.

1. Introduction

1.1. General remarks

It is well known that the superplastic flow is a form of high-temperature creep, therefore the deformation process is thermally activated and the flow rate is strongly stress dependent [1–3]. These processes can be characterized by the double logarithmic plot of the applied true stress versus true strain rate at constant temperature. According to the experimental results, the mechanical behaviour of the superplastic materials can be divided into three parts [1]. At low stresses (region I) and at high stresses (region III) the strain-rate sensitivity parameter is low and the process is not superplastic. Superplastic deformation occurs only at intermediate stresses where the strain-rate sensitivity is higher than 0.3.

The high-temperature creep rate, $\dot{\varepsilon}$, of pure metals and alloys can be described by the equation

$$\dot{\varepsilon} = A\sigma^{n_a} \exp(-Q_a/kT) \qquad (1)$$

where σ is the applied stress, A is a material parameter, n_a is the apparent stress exponent which is the inverse of the strain-rate sensitivity parameter, and Q_a is the apparent activation enthalpy. Using Equation 1, the apparent stress exponent and the apparent activation energy can be evaluated from the expressions

$$n_a = \left.\frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma}\right|_T \qquad (2)$$

$$Q_a = -k\left.\frac{\partial \ln \dot{\varepsilon}}{\partial (1/T)}\right|_{\sigma, n} \qquad (3)$$

respectively. It is well supported that the experimental data in every region of the stress–strain curve can be fitted to Equation 1. Naturally, the n_a and Q_a values belonging to the three regions are, in general, different from each other [4, 5].

1.2. Threshold stresses in superplastic materials

In certain alloys the activation enthalpies of the creep processes are significantly higher than the self-diffusion energy of the matrix. In some cases, a more realistic stress exponent and activation enthalpy can be obtained if the creep process is described in terms of an effective stress, σ_e, which is the difference between the applied stress, σ, and a threshold stress, σ_0. Then the creep rate can be expressed by the modified form of the rate equation (Equation 1)

$$\dot{\varepsilon} = A(\sigma - \sigma_0)^n \exp(-Q/kT) \qquad (4)$$

This concept was successfully applied for the description of the deformation process of some superplastic materials [6].

There is sufficient experimental evidence for the existence of a threshold stress in Pb–62 % Sn [6] and Zn–22 % Al [6, 7], as well as in some more complex aluminium alloys [8], and it was also shown that in all of these cases the threshold stress exhibits a strong temperature dependence. This temperature dependence leads to a change of the activation enthalpy determined on the basis of Equation 1. Therefore, to obtain the true activation enthalpy which is characteristic to the micromechanism of the process, the value of the apparent activation enthalpy must be corrected.

1.3. Correction of the activation enthalpies using the temperature dependence of the threshold stress

Such correction was applied originally for the analysis of creep data of dispersionally strengthened copper alloys where extremely high activation energies were obtained experimentally with the use of Equation 1 [9]. Taking into account the temperature dependence

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of the threshold stress in the form

$$\sigma_0 = B\exp(Q_0/kT) \tag{5}$$

it can be shown that there is a simple relationship between the true and apparent value of the strain-rate sensitivity and similarly a simple connection is valid for the true and apparent activation enthalpies [7, 10]. The relationships are

$$n = n_a\left(1 - \frac{\sigma_0}{\sigma}\right) \tag{6}$$

and

$$Q = Q_a - \frac{nQ_0}{(\sigma/\sigma_0) - 1} \tag{7}$$

With the use of these equations a simple connection can be made between the true and apparent activation enthalpy

$$Q = Q_a - (n_a - n)Q_0 \tag{8}$$

The apparent value of these quantities can be evaluated in the usual way from the double logarithmic plot of the $\dot{\varepsilon}$–σ function determined experimentally. Rearranging the data in an $\dot{\varepsilon}^m$–σ plot, where m is chosen as a best-fit parameter for Equation 4, the threshold stresses are given by the intercepts of the straight lines obtained. On the basis of Equation 5, Q_0 can be calculated from the slope of the $\ln\sigma_0$ versus $1/T$ graph, and Q can be determined from these data with the use of Equation 7. Until now, this method has been used for the determination of the true activation energy of the superplastic processes [6–8, 10–12].

The most crucial point of the procedure described above is the determination of the true stress exponent. However, the rate equation (Equation 1) enables us to estimate the true stress exponent. Namely, according to Equation 6 at high stresses the apparent stress exponent tends to the true one. Thus, $n = n_a$, determined at the high stress part of region II from the double logarithmic plot of the σ–$\dot{\varepsilon}$ function, can be regarded as a relatively good approximation of the true stress exponent.

In this paper a new procedure is proposed for the determination of the true activation energy of processes including a strongly temperature-dependent threshold stress. The results obtained will be compared with those obtained using the conventional method.

2. Activation energy determination based on the slope of the σ–$\dot{\varepsilon}^m$ plot

To eliminate the difficulties caused by the theoretical and practical problems connected with the temperature dependence of the threshold stresses, a new method was developed for the evaluation of the true activation energy. Let us rewrite Equation 4 in the form

$$\sigma = \sigma_0 + (1/A^m)\exp(mQ/kT)\dot{\varepsilon}^m \tag{9}$$

Plotting σ against $\dot{\varepsilon}^m$, a straight line is obtained with slope

$$C = A'\exp(mQ/kT) \tag{10}$$

where $A' = (1/A)^m$. Plotting again $\ln C$ as a function of $1/T$, the slope of the straight line gives the true activation enthalpy. To illustrate this procedure, the results of impression creep measurements made on AlZnMg alloys are used. Fig. 1 shows the pressure applied as a function of the steady-state punch velocity. These quantities are in a simple relation with the stress and strain rate of the tensile creep test ($\sigma = p/3$, $\dot{\varepsilon} = v/d$ where d is the diameter of the punch). Fig. 2 shows the $\ln C$–$1/T$ plot obtained using the data of Fig. 1.

It is worth emphasizing that this procedure is based (instead of the determination of the threshold stress) on the knowledge of the slope of the σ–$\dot{\varepsilon}^m$ curve. This means that this method permits determination of the true activation enthalpy not only without the assumption of the explicit temperature dependence of the threshold stress (as in Equation 5) but even without the knowledge of it. This method can be equally applied in the case if the threshold stress is zero and if it has a finite value. Naturally, if the former alternative occurs, then the true activation energy should be equal to the apparent one.

We have also reanalysed the data of our previous paper [10] obtained by impression creep testing, and the tensile measurements of Malek [11] from Al–Zn–Mg–Cu alloys with various chromium contents. Both measurements revealed the occurrence of a strongly temperature dependent threshold stress leading to the unification of regions I and II. This unification indicates the same true stress exponent and activation energy for the first two regions. In Fig. 3 the

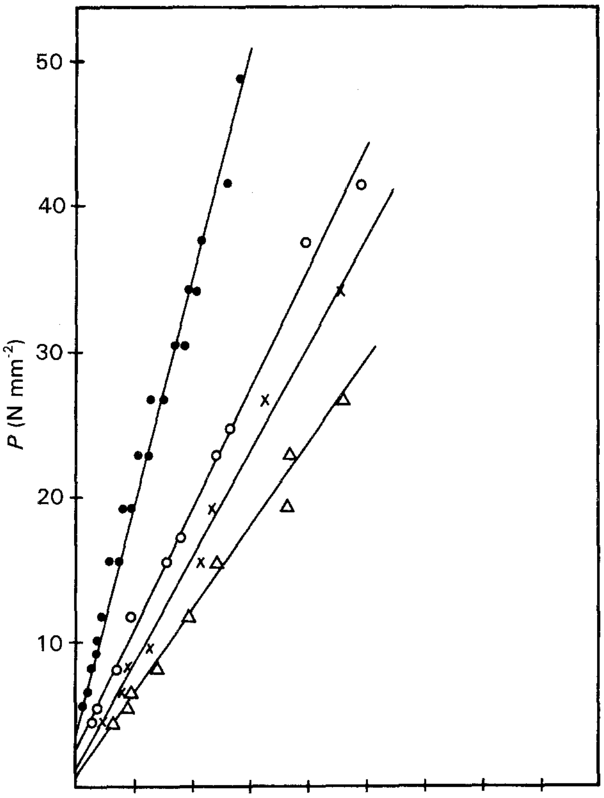

Figure 1 The P–v^m functions of an AlZnMg alloy at different temperatures: (●) 673 K, (○) 698 K, (×) 718 K, (△) 735 K.

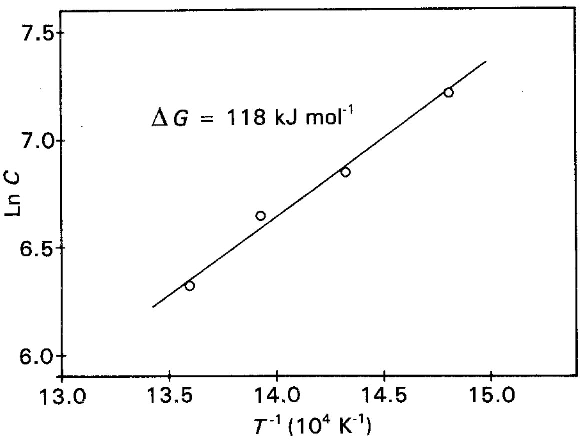

Figure 2 Determination of the true activation enthalpy using the lnC–$1/T$ plot obtained from the data of Fig. 1.

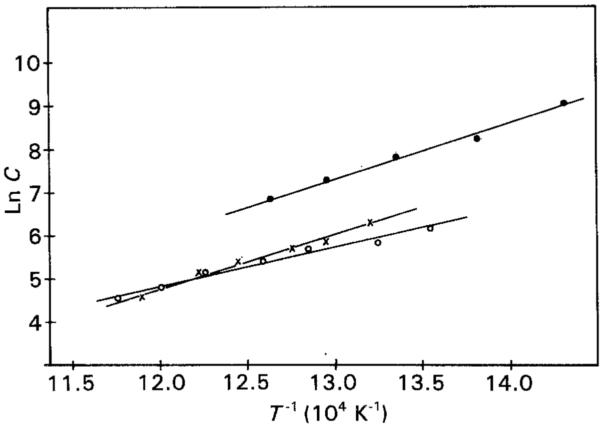

Figure 3 The lnC–$1/T$ plot for alloys with different chromium contents: (●) 0.15 wt % Cr, Q = 140 kJ mol^{-1}, m = 0.76 [11]; (○) 0.25 wt % Cr, Q = 163 kJ mol^{-1}, m = 0.50 [10]; (×) 0.4 wt % Cr, Q = 240 kJ mol^{-1}, m = 0.45 [10];

previous data [10, 11] are replotted as an ln$C$–$1/T$ function and the respective values of the activation energies are also shown.

The results obtained for the activation energy by the present evaluation agree fairly well with those obtained earlier. Therefore, both the sections and the slopes of the σ–$\dot{\varepsilon}^m$ curves give suitable data for the determination of the true activation energy of the superplastic processes. The good agreement of the results obtained by the two different methods gives well-established evidence for the existence of a temperature-dependent threshold stress in some superplastic materials and indirectly supports the validity of the exponential temperature dependence of the threshold stress for the alloys in question [6].

3. The effect of the chromium content on the activation enthalpy

It is known that in some aluminium alloys, extremely high apparent activation enthalpies are obtained for the superplastic process [7, 11, 12]. Taking into account the existence of a threshold stress, more reliable activation enthalpies are obtained, although the corrected values are also significantly higher than the self-diffusion energy of aluminium. As an example, in Fig. 4 the corrected activation enthalpies of AlZnMg alloys with different chromium contents are plotted against the chromium concentration. It can be seen that the activation enthalpy decreases with decrease of the chromium content and approximately tends to the self-diffusion energy of aluminium.

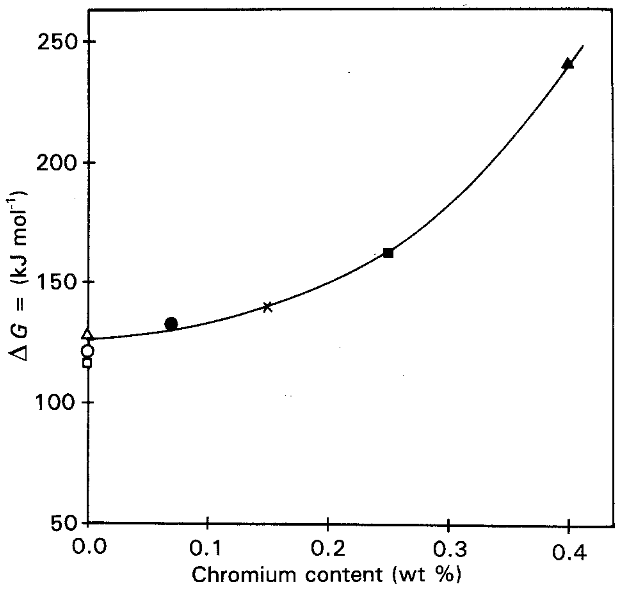

Figure 4 The true activation enthalpy as a function of the chromium content: (●) 0.07 wt % Cr, (×) 0.15 wt % Cr, (■) 0.25 wt % Cr, (▲) 0.4 wt % Cr. (△, ○, □) Alloys with no chromium content.

These results have affirmed our earlier findings that the activation energy of the superplastic processes can be increased by dispersionally distributed precipitates which are incoherent with the matrix [10]. It is probable that in the alloys investigated, the superplastic flow is controlled by grain-boundary sliding and this latter process is highly influenced by particles with a chromium content. These particles are probably incoherent with the matrix [13] and are pinning the grain boundaries very effectively.

4. Conclusions

1. A new method is presented for the evaluation of the true activation enthalpy for creep processes involving a temperature-dependent threshold stress. The procedure exploits the temperature dependence of the slope of a double linear plot of the applied stress versus strain rate raised to the power of the true strain-rate sensitivity parameter, and makes it possible to determine the activation enthalpy without knowledge of the explicit form of the threshold stress.
2. The data of some earlier measurements on superplastic AlMgZnCu alloys with different chromium contents have been reanalysed by this method and the results obtained are in good agreement with those given earlier.
3. The true activation enthalpy of the set of alloys studied decreases with decreasing chromium content.

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References

1. T. G. LANGDON, *Met. Trans.* **13A** (1982) 689.
2. B. P. KASHYAP, A. ARIELI and A. K. MUKHERJEE, *J. Mater. Sci.* **20** (1986) 2661.
3. O. D. SHERBY, *ISIJ Int.* **29** (1989) 698.
4. F. A. MOHAMED, S. A. SHEI and T. G. LANGDON, *Acta Metall.* **23** (1975) 1443.
5. T. G. LANGDON, *Mater. Sci. Eng.* **A137** (1991) 1.
6. F. A. MOHAMED, *J. Mater. Sci.* **18** (1983) 582.
7. *Idem*, *J. Mater. Sci. Lett.* **7** (1988) 215.
8. P. K. CHAUDHURY, V. SIVARAMAKRISHNAN and F. A. MOHAMED, *Metall. Trans.* **19A** (1988) 2741.
9. B. BURTON, "Diffusional Creep of Polycrystalline Materials", Diffusion and Defect Monograph Series (Trans. Tech., Switzerland, 1977) p. 73.
10. N. Q. CHINH, A. JUHÁSZ, P. TASNÁDI and I. KOVÁCS, *J. Mater. Sci.* **25** (1990) 4767.
11. P. MALEK, *Mater. Sci. Eng.* **A137** (1991) 21.
12. G. S. MURTY and M. J. KOCZAK, *ibid.* **96** (1987) 117.
13. H. WESTENGEN, O. REISO and L. AURAN, *Aluminium* (1981) 768.

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