High Temperature Behavior of Zinc Alloys

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CONTENTS

Abstract

Hart's phenomenological equation of state is used to describe the plastic deformation (secondary creep rate, extrusion) and creep fracture of zinc and zinc alloys by introducing the Zener-Hollomon or the Dorn parameters. The results are compared with those obtained by current parametric methods or the hyperbolic sine law.

Introduction

Behavior consistent with Hart's equation of state /1/ has been observed on a wide variety of metals with different structures. At high homologous temperature, the Hart equation may be expressed by the following relations:

$$\ln (\sigma/\sigma^*) = (\dot{\varepsilon}/\dot{\varepsilon}^*)^{\lambda} \quad (1)$$

$$\dot{\varepsilon}^* = (\sigma^*/G)^m \, f \, \exp(-Q/RT), \quad (2)$$

where σ^* is a structural parameter called the "hardness"; $\dot{\varepsilon}^*$ is an auxiliary parameter which depends on temperature, heat treatment and deformation; T is the absolute temperature; R is the gas constant; G is the modulus of rigidity at temperature T; and λ, f, m. and Q are constants for each material.

The rate of deformation in regions where Eqs. 1 and 2 apply is assumed to be controlled by a diffuse process, and $\log\sigma$-$\log\dot{\varepsilon}$ curves appear concave downward. The curves for different hardnesses at a given temperature are related through translation along a straight line in the σ-$\dot{\varepsilon}$ log-log space. The slope of the translation path is $\mu=1/m$. The curves for different temperatures at a given hardness are related through translation along the $\dot{\varepsilon}$ axis using a standard Arrhenius rate equation.

It is the purpose of this paper to use Eqs. 1 and 2 to interpret data found in the literature on creep and extrusion of zinc and zinc alloys.

Materials

Creep experiments were performed /2/ on a zinc-0.59%Cu-0.19%Ti alloy rolled on an industrial rolling mill at temperatures from 298 to 373 K. With a stress range from 48 to 133 MPa, the rupture life extends from 10 hours to about 3000 hours. Time-to-rupture, time for producing a 1% total elongation, and minimum creep rate were reported. The results were analysed by the authors in terms of the Larson-Miller parameter.

Gagnon and Jonas /3/ investigated the extrusion of 99.99+ zinc between 0.55 and 0.9 Tm, where Tm is the melting temperature. The stress range was 16 to 135 MPa, and the range of mean equivalent strain rate was 0.0635 to 5.04 s^{-1}. The results were analysed by the authors in terms of the hyperbolic sine law.

Methods

To interpret the rupture time in creep experiments, the Dorn parameter, Θ, was first introduced by Johnson, Straaslund and Wire /4/. By substituting $\Theta = t_r \exp(-Q/RT)$ in Eqs. 1 and 2 and assuming a relation between rupture time and minimum creep rate as: $t_r = \varepsilon_r/\varepsilon_{ss}$, they obtained:

$$\log \Theta = A + (1/\lambda) \log\log (\sigma^*/\sigma) \quad (3a)$$

or

$$\log t_r = B(1) + B(2)/RT + B(3) \log\log (\sigma^*/\sigma) \quad (3b)$$

where the coefficients are calculated by linear regression analysis about σ^* to minimize the sum of the square of the residuals.

In creep experiment (minimum creep rate) and in extrusion, we introduce the Zener-Hollomon parameter $Z = \dot{\varepsilon} \exp(Q/RT)$. On substituting this latter expression into Eqs. 1 and 2, the following expression is obtained:

$$\log Z = A' - Q/RT - (1/\lambda) \log\log (\sigma^*/\sigma) \quad (4a)$$

which may also be written:

$$\log \dot{\varepsilon} = B'(1) + B'(2)/RT + B'(3) \log\log (\sigma^*/\sigma) \quad (4b)$$

This equation has an equivalent form as Eq. 3, and the coefficients are also calculated by multilinear regression with $\dot{\varepsilon}$, T and σ.

Results

A. Secondary Creep Rate of Zinc Alloys

Using available experimental data /2/, the creep stress is plotted logarithmically as a function of the minimum creep rate, $\dot{\varepsilon}ss$ for each temperature (Fig. 1a). The curves can be intrerpreted in the sense of temperature-compensated strain rate; so it is possible to superpose by translation along the $\dot{\varepsilon}$ axis any one of the curves onto any of the others in such a way that the overlapping segments of each curve match with experimental error (Fig. 1b). Such a master curve can be obtained directly by introducing the Zener-Hollomon parameter (Eq. 4). This curve is displayed in Fig. 1c. In Fig. 1a, the number of data at each temperature, 5 to 7, is insufficient to calculate the corresponding equation. By introducing the Zener-Hollomon parameter, the regression is performed with all the data, 31, and it is possible to compute the coefficients of Eq. 4 and then the equation of each individual curve of Fig. 1a. Examination of the curves indicates that for a given temperature the experimental data (symbols) are in very good agreement with the curves plotted from Eq. 4. By translation or by using the Zener-Hollomon parameter, we obtained the same apparent activation energy: Q = 25.7 Kcal/mole.

B. Rupture Time of Zinc Alloys

Eq. 3 is applied to the data of Habraken et al. /2/ on Zinc-Copper-Titanium alloys. By using Eq. 3 a linear relation can be established between the Dorn parameter and log (σ^*/σ) in the log-log coordinates (Fig. 2a) or, equivalently, the master curve $\ln\sigma$-$\ln\Theta$ (Fig. 2b). In the same way, the stress $\sigma 1\%$ associated with a 1% strain is related to the time t (Fig. 2b).

As far as we know, the method used by Johnson et al. /4/ was never used by other authors except in our previous work on 1Cr and 19Cr steel /7/ and 12Cr steel and S590 alloy /5-6/. In the latter, we compared the prediction obtained from Eq. 3 and from classical parametric methods (Larson-Miller, Sherby-Dorn, Manson-Harfed) on the Goldhof data on S590. All predictions are in very good agreement. One of the advantages of the method we used is to give the equation of the master curve so that extrapolations are possible (but dangerous). On the other hand, with parametric methods the curves are fitted by a polynomial equation and inflection points can be found. Eq. 3 can also be applied to relate the stress $\sigma x\%$ to the time at which the strain is x%. This method holds only when x% is sufficient (the primary creep stage must be negligeable). The coefficient B(2) is related to the activation energy. The value we found, 25.5 Kcal/mole, is in fairly good agreement with those reported by using the Larson-Miller parameter /2/ and corresponds to the activation energy for self-diffusion /11/.

C. Extrusion of Pure Zinc

Data from Gagnon and Jonas /3/ are considered to illustrate the use of Hart's equations. Fig. 3a shows the satisfactory linear relationship obtained between the logarithm of log (σ^*/σ) and the logarithm of the Zener-Hollomon parameter. The coefficients B'(1), B'(2) and B'(3) were calculated and, according to Eq. 4b, the master curve is obtained as a plot of the logarithm of the mean flow stress vs. the logarithm of the mean equivalent strain rate in Fig. 3. For individual temperature experiments, the variation of the logarithm of the stress vs. the logarithm of the strain rate is plotted in Fig. 3c. Examination of the solid lines in Fig. 3c indicates the good correlation between experimental data from Gagnon and Jonas /3/ and theoretical curves derived from Hart's equation.

The relation between stress and strain rate during extrusion is generally analysed according to the

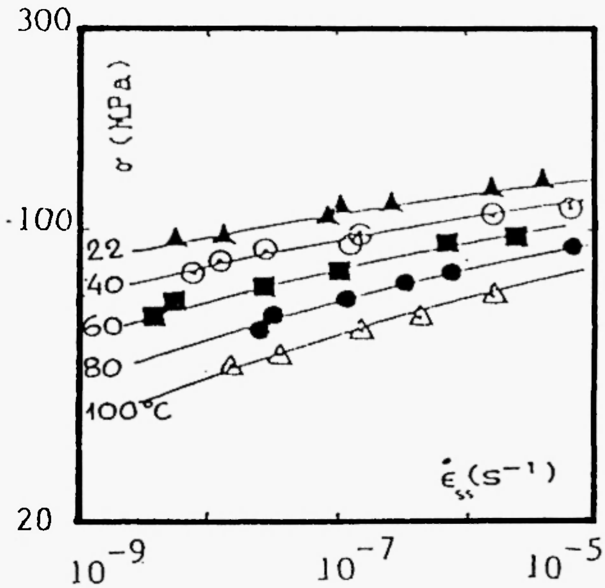

Fig. 1a: Based on data in Habraken et al. /2/ on zinc-0.59%Cu-0.19%Ti alloy. The variation of the logarithm of the stress is plotted against the logarithm of the secondary creep rate for all temperatures investigated.

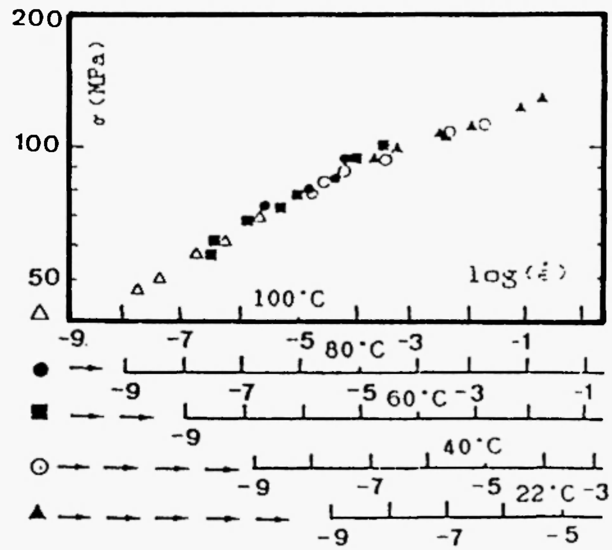

Fig. 1b: By translating along the $\dot{\varepsilon}$ axis the curves of Fig. 1a superposed to form a master curve.

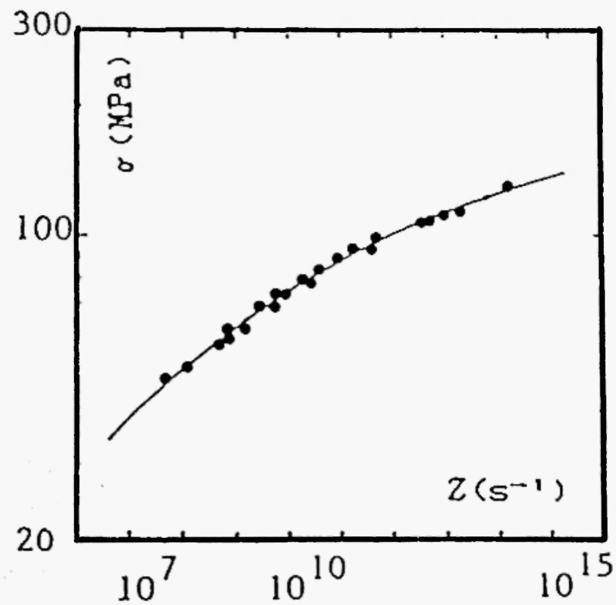

Fig. 1c: The master curve is obtained directly by multilinear regression from Eq. 4.

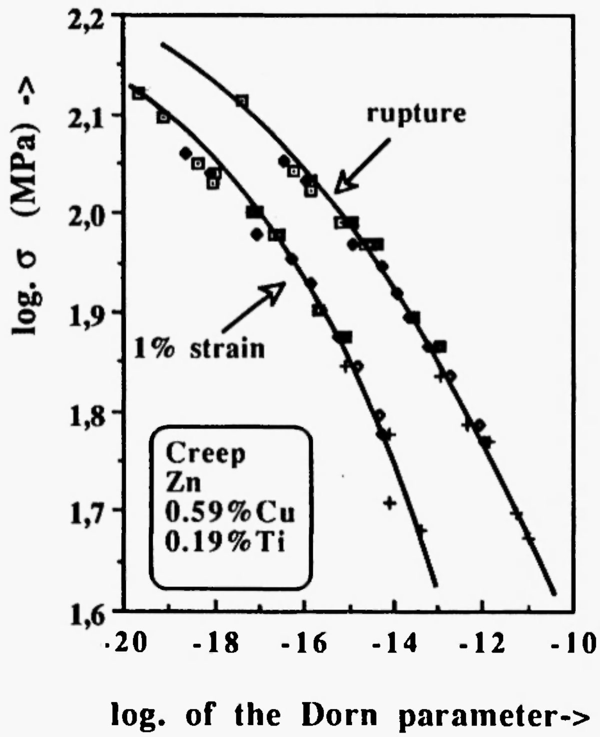

Fig. 2a: Based on data in Habraken et al. /2/ on creep of zinc-0.59%Cu-0.19%Ti alloy, the variation of the logarithm of log (σ^*/σ) is plotted against the logarithm of the Dorn parameter.

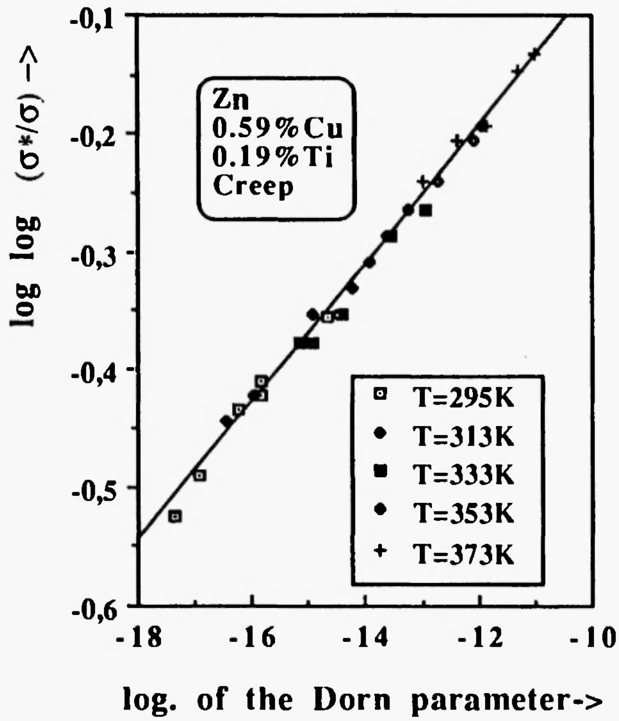

Fig. 2b: The master curve: logarithm of the creep stress vs. logarithm of the Dorn parameter (or logarithm of the rupture time) is deduced from Fig. 2a. The results concerning the time to obtain 1% strain are also indicated.

following sine relationship:

$$\varepsilon = A_1 [\sinh(\alpha\sigma)]^{n_1} \exp[-Q/RT] \qquad (5)$$

It should be noted that the curves (logσ vs. log$\dot{\varepsilon}$) plotted from Eqs. 4b and 5 superposed for all the experimental range investigated. The activation energy we found (26.7 Kcal/mole) is also in good agreement with the value of 28 Kcal/mole obtained by other investigators /3/ when adiabatic heating is neglected.

Discussion

All experimental data we used in this study are taken from the literature and correspond to experimental works performed without the refinements proposed by Hart /9/. A great number of results are available in previous works and may be expressed by Hart's phenomenological equations. Only the early stage of the experiments are lost, but that has no importance for the long time data we investigated.

- Creep rupture time, creep secondary strain rate, creep stress and extrusion data may be related usefully for design purposes by Hart's equations (Eqs. 1 and 2).
- The temperature dependence may be described simply by the Dorn or the Zener-Hollomon parameters which allow the calculation of the coefficients: λ, Q and $\dot{\varepsilon}^*$ from linear plot of the logarithm of log (σ^*/σ) against the logarithm of the appropriate parameter. The coefficients are opti-

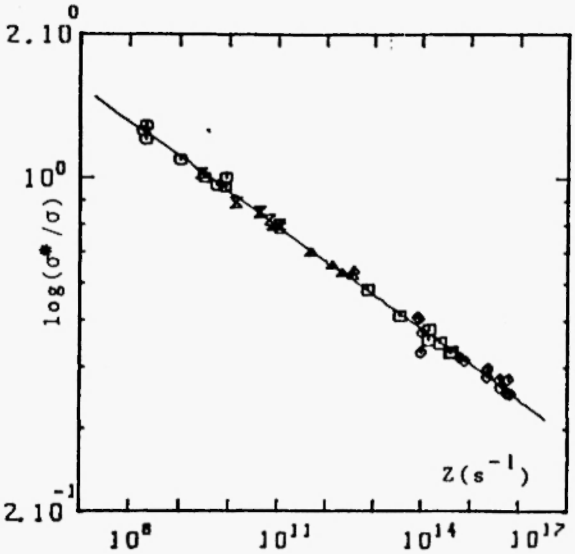

Fig. 3a: The log-log (σ^*/σ) vs. logZ relationship from the experimental data of Gagnon and Jonas /3/ on extrusion of 99.99+ zinc.

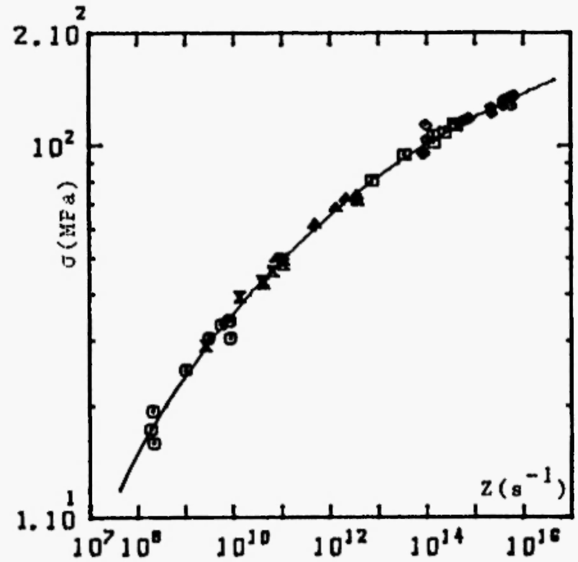

Fig. 3b: The master curve plotted from coefficients calculated by Eq. 4b.

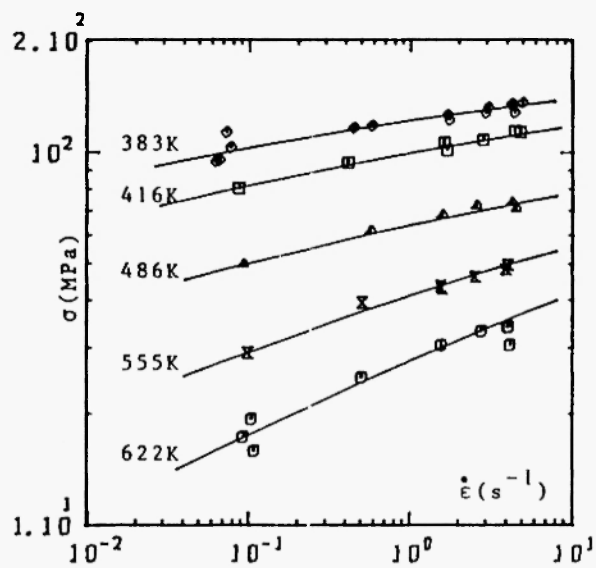

Fig. 3c: Predicted variation of log-σ vs. log-$\dot{\varepsilon}$ for each temperature and comparison with experimental data.

Table 1

Results obtained by multilinear regression on the different alloys investigated

Method	Material	σ* (MPa)	λ	Q(Kcal/mole)
translation	Zn-0.59%Cu-0.19%Ti			26
Zener-Hollomon	Zn-0.59%Cu-0.19%Ti	226	226	25.7
Dorn (rupture)	Zn-0.59%Cu-0.19%Ti	258	258	25.5
Dorn (1%)	Zn-0.59%Cu-0.19%Ti	196	196	25.7
Zener-Hollomon	Zn 99.99%+	292	292	26.7

mized by a multilinear regression to minimize σ^*. The results are reported in Table 1.

- From Table 1 the following constatations can be made:
  - λ has the value 0.6-0.8. This is contrary to the majority of published data, which generally show a constant value λ=0.15. Such a result was previously found in the literature, 0.085 for Zry-4 /10/.
  - Previous experimental results have shown that the hardness parameter σ^* is related to the yield stress at low temperature. This is generally what we observed, but in some cases σ^* is found to be very different (for example, 4950 MPa for creep rupture test of S590 alloy /5/).
  - Activation energies are very similar and close to the activation energy for self-diffusion in

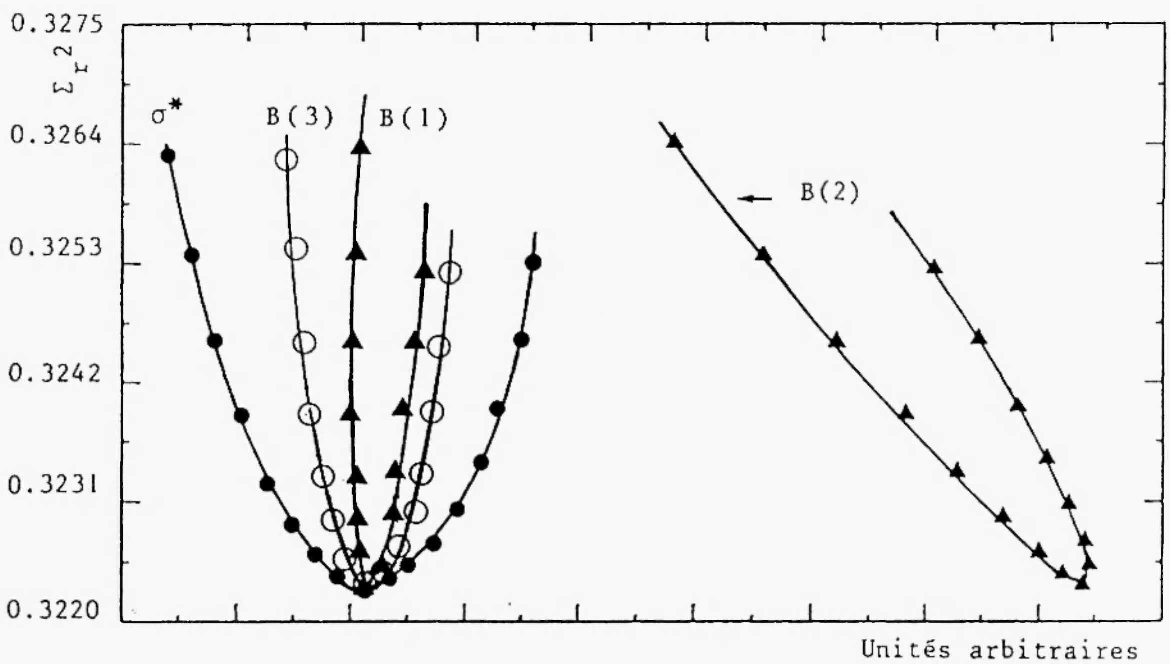

Fig. 4: Minimum of the square of the residuals vs. σ^*, B'(1), B'(2) and B'(3) for minimum creep rate in zinc-0.59%Cu-0.19%Ti alloy interpreted by means of Eq. 4b.

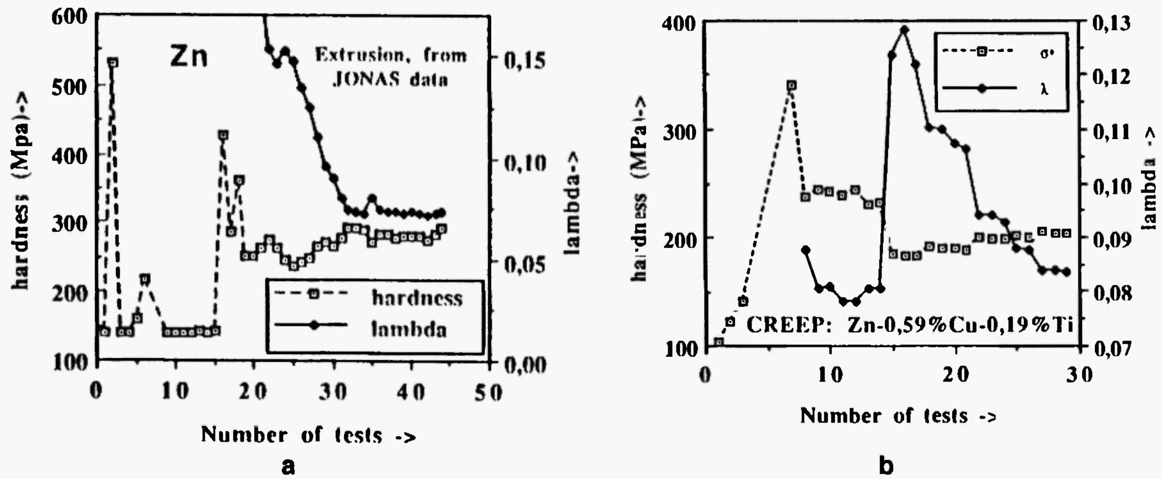

Fig. 5: Variation of σ^* and λ in Eq. 4a with the number of experiment (with increase of Z) for zinc extrusion (a) and Zn-Cu-Ti creep (b).

zinc and zinc alloys; 22.4 Kcal/mole /11/.

- Results obtained for creep (rupture time, time corresponding to a 1% strain and secondary creep rate) are in fairly good agreement with those obtained by the classical parametric methods.
- Results obtained for extrusion are in fairly good agreement with those interpreted by the hyperbolic sine law. For torsion experiments performed on AISI 304 steels, we always show the good correlation between Eq. 4 and hyperbolic sine law /8/.
- Questions are often raised on the validity of the log-log regression. Fig. 4 shows that the minimum of the square of the residuals is clearly indicated for the optimal value of the hardness parameter, σ^*.
- Questions are often raised on the number of experiments needed to obtain a good prediction with the use of classical parametric methods. From Eqs. 3 and 4, calculation of σ^*, Q, λ and Σr^2 in relation with the number of tested specimens is obvious.

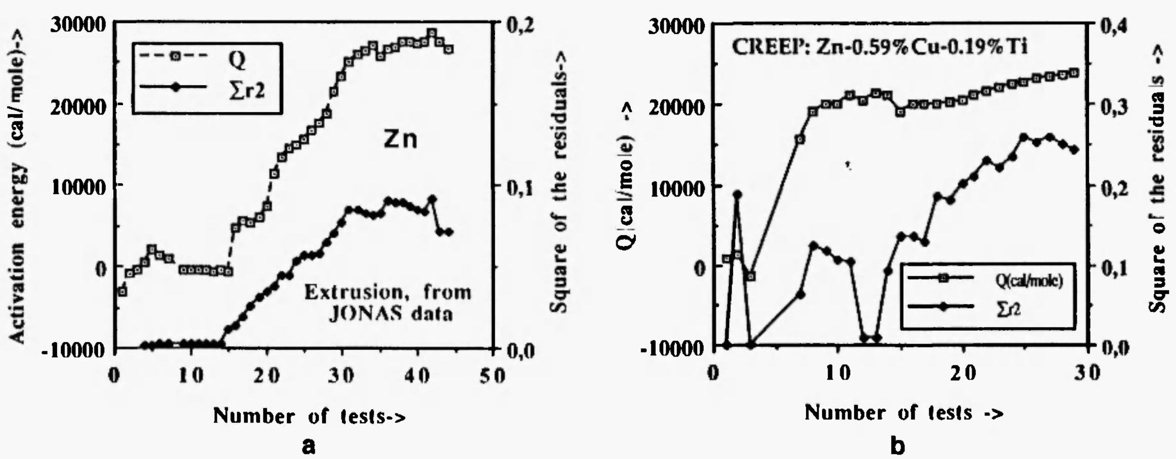

Fig. 6: Variation of Q and of the minimum of the square of the residuals in Eq. 4a for zinc extrusion (a) and Zn-Cu-Ti creep (b).

Figs. 5 and 6 show the variations of these coefficients for zinc extrusion data when the data are classified by a rising Zener-Hollomon parameter and for creep fracture of Zn-Cu-Ti alloys when the data are classified by a rising Dorn parameter. All coefficients stabilize and tend to limiting values when the number of data is at least 35. In some materials, two limiting values can be found that can be interpreted by the presence of two mechanisms.

Conclusions

Creep experiments on Zn-Cu-Ti alloys and extrusion tests of zinc show that these materials have a mechanical equation of state at high homologous temperature. By introducing the Zener-Hollomon and the Dorn parameters, the equation we obtained compared well with the classic parametric methods (Larson-Miller) or the hyperbolic sine law. The advantages are a better prediction and the knowledge of the master curve equation.

Acknowledgements

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