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Constitutive Description of Creep Behavior of Mg–4Al–1Ca Alloy

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Creep behavior of an advanced magnesium alloy AX41 (4 wt.% Al, 1 wt.% Ca, Mg balanced) was investigated in temperature interval from 343 to 673 K and stresses from 2 to 200 MPa. Compressive creep experiments with stepwise loading were used in order to obtain stress dependence of the creep rate in interval from 10^{-9} to 10^{-3} s^{-1} for a given temperature. All stress dependences can be well described by the Garofalo sinh relationship with natural exponent $n = 5$. An analysis of the parameters of this relationship has shown that lattice diffusion controls creep at all experimental conditions. While climb-controlled creep mechanism is decisive at lower stresses and higher temperatures, glide-controlled mechanisms act at higher stresses and lower temperatures. A typical power-law breakdown is observed at intermediate stresses and temperatures.

Keywords: magnesium alloys, creep, constitutive creep equation of creep, creep mechanisms.

Introduction. The Mg–Al–Ca alloys are developed as a cheaper alternative of the alloys containing rare earth metals for applications at elevated temperatures. Mechanical properties of these alloys, namely their creep resistance, are improved by precipitates of $Mg_{17}Al_{12}$ and Mg_2Ca. However, effective development of this type of magnesium alloys is impeded by the lack of experimental data as well as detailed knowledge of mechanisms governing their creep behavior at elevated temperatures. In the present study, some results of creep behavior investigation of a representative of this alloy group, i.e., the alloy AX41, are summarized for a wide interval of temperatures and stresses.

Experimental. Magnesium alloy AX41 with nominal composition (in wt.%) 4 Al, 1 Ca and Mg balanced was cast in Zentrum fьr Funktionwerkstoffe in Clausthal-Zellerfeld, Germany. Parallelepiped specimens with 6×6 mm cross section and 12 mm height were annealed at 673 K for 24 h and cooled in air and then heated at 353 K for 16 h. The average size of regular grains $d = 0.037$ mm resulted from the high temperature treatment.

Compressive creep tests with stepwise loading were used, in order to obtain stress dependence of the creep rate in interval from 10^{-9} to 10^{-3} s^{-1} for a given temperature. In any step, the constant loading was hold until the creep rate reached stationary or quasi-stationary value. This rate was then assigned to the true stress σ corresponding to the last strain value in the step. The loadings of consequent steps were chosen randomly. The tests were mostly conducted till the strain reached a value $\varepsilon = 0.15$. Suitability of the used stepwise procedure was verified by a comparison of obtained creep rates at a given stress level with those resulting from conventional compressive tests under constant stress. Differences of these values lay in scatter error.

The tests were performed in purified and dried argon atmosphere. Identical temperature regime was applied before each test in order to eliminate eventual influence of temperature on second phase's precipitation during the test. In all cases, the sample was kept approximately 10 h at the testing temperature before the test was started. The strain was measured with the sensitivity 10^{-5}. For the stepwise stress creep experiments and evaluation of their results, special software was developed.

Results. Creep behavior of the alloy was investigated at temperatures from 343 to 673 K. Stress dependences of the creep rate $\dot{\varepsilon}$ are illustrated in both conventional coordinate systems, i.e., bi- and semi-logarithmic, in Fig. 1a and 1b. From the shape of dependences, no simple relationships, power law or exponential, can be chosen for their description in the entire experimental interval of conditions. For small stresses and higher temperatures the Norton power-law relation

$$\dot{\varepsilon} \propto \sigma^n \tag{1}$$

with $n \cong 5$ seems to be suitable for the description, the exponential relationship can be rather well applied at lower temperatures and higher stresses. At intermediate testing conditions, neither of both relationships is applicable. In principle, such behavior can be well described by Garofalo's sinh formula, which is conforming to both these basic descriptions in accord with above stress dependence of the rate $\dot{\varepsilon}$.

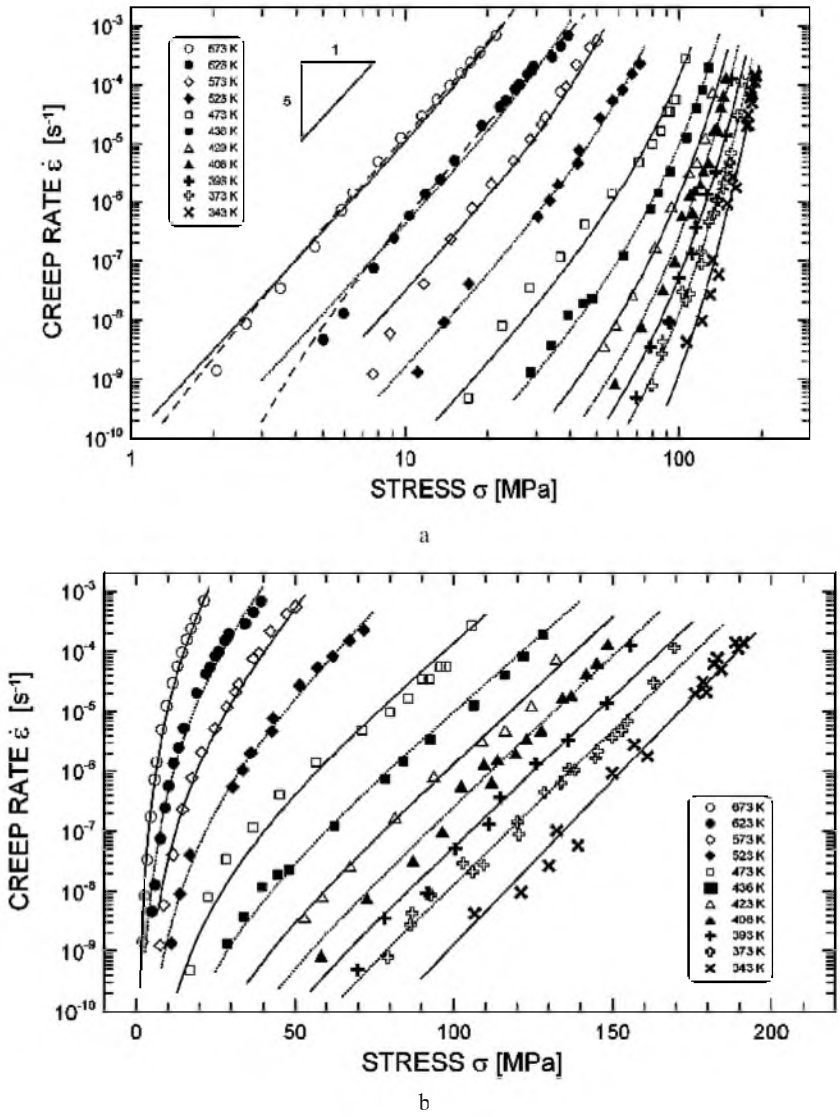

Fig. 1. Stress dependences of creep rate in bi-logarithmic (a) and semi-logarithmic (b) coordinates.

The Garofalo equation has a form [1]

$$\dot{\varepsilon} = A(\sinh[B\sigma])^n , \tag{2}$$

where parameters A and B depend on temperature T only and exponent n is considered to be natural number and temperature dependence of the parameter A can be written as

$$A \propto \exp\left[-\frac{Q}{RT}\right], \tag{3}$$

where Q is the activation energy and R the gas constant. For values $B\sigma \leq 0.8$, Eq. (2) transfers to power-law relationship with stress exponent n and for $B\sigma \geq 1.2$ to the exponential relationship with the function argument $nB\sigma$.

Values of the exponent n from 3 to 7 were proved in data treatment. Statistically, the best agreement was obtained by description for the exponent $n = 5$. Using this value, optimum treatment of the stress dependences of the rate $\dot{\varepsilon}$ has confirmed good applicability of both Eqs. (2) and (3) – see drawn curves in Fig. 1a and 1b which correspond to these equations.

Dependence of the parameter A on reciprocal temperature is plotted in Fig. 2. A straight line can be drawn through calculated values in chosen coordinate system, which confirms validity of Eq. (3). The activation energy $Q = 137$ kJ/mol results from the slope of the straight line. This value is very close to the activation enthalpy of self-diffusion of magnesium $\Delta H_{SD} = 135$ kJ/mol [2].

Temperature dependence of the parameter B is plotted in the Fig. 3. The dependence has a convex shape; the parameter B reaches values from 0.021 to 0.035 with the minimum at approximately at 450 K.

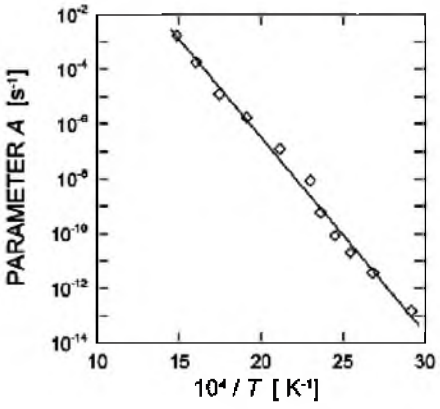

Fig. 2

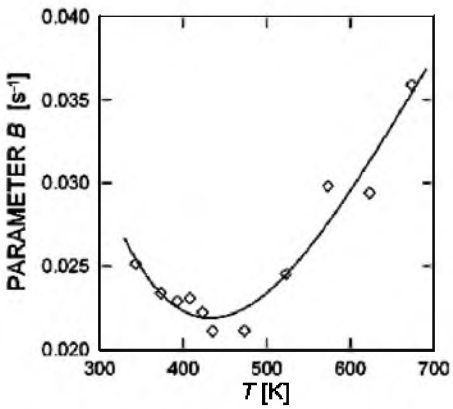

Fig. 3

Fig. 2. Temperature dependence of the parameter A.
Fig. 3. Temperature dependence of the parameter B.

Discussion. The activation energy Q obtained from temperature dependence of parameter A [cf. Fig. 2 and Eq. (3)] is very close to the activation enthalpy of lattice diffusion in Mg. Probably, there are no data of diffusion in the investigated magnesium alloy AX41. However, it can be expected that the enthalpy of lattice diffusion in the investigated alloy does not differ substantially from that in pure magnesium. Therefore, one can assume that the value of the energy Q supports an expectation that the creep behavior of the alloy is controlled by diffusion processes under all experimental conditions.

A natural exponent $n = 5$ was revealed to be the most convenient stress exponent in the power-law part of the stress dependences of the creep rate $\dot{\varepsilon}$. From phenomenological point of view, such exponent is usually connected with the metal-type (Class II) creep behavior [3]. As the most probable mechanism controlling creep, respecting also the value of the energy Q, combined mechanism of climb and glide of dislocations can be considered (see e.g., [4]).

Exponential expression of the stress dependences of rate $\dot{\varepsilon}$ is frequently attributed to thermally activated glide of dislocations. With respect to the controlling role of lattice diffusion, the non-conservative glide should be the major mechanism in the interval of the validity of exponential dependence. A very simple concept of non-conservative motion of jogs on screw dislocation segments [5] can be accepted. Then, the apparent activation energy of creep $Q_c = [-\partial \ln \dot{\varepsilon}/\partial(1/RT)]_\sigma$ should depend on the stress due to the temperature dependence of the parameter B.

It can be seen from Fig. 1a that the shape of stress dependences at the highest temperatures indicates possible threshold behavior since a strong bend of the rate $\dot{\varepsilon}$ towards lower values appears when the stress decrease to a certain value (~ threshold stress σ_{th}). Therefore, an attempt was performed to describe these dependences by the modified Garofalo relationship

$$\dot{\varepsilon} = A\{\sinh[B(\sigma - \sigma_{th})]\}^5, \tag{4}$$

which are illustrated in Fig. 1a by dashed lines drawn for 673 and 623 K. However, acceptable positive values of σ_{th} were obtained from optimizing procedures only at temperatures from 473 to 673 K.

Conclusions. Following conclusions can be drawn from the investigation of creep behavior of the AX41 alloy in temperature interval from 343 to 673 K:

- Stress dependences of the minimum creep rate $\dot{\varepsilon}$ can be well described by the Garofalo equation (2).
- Obtained parameters of this relationship can be well physically interpreted.
- Lattice diffusion controls creep behavior of the AX41 alloy in the entire experimental interval.

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