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Modeling of High-Temperature Deformation of Commercial Pure Aluminum (1050)

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The high-temperature deformation of commercial pure aluminum (Al) (1050) was investigated by performing tensile tests in the temperature range of 473-673 K at initial strain rates of 0.01-0.2 s^{-1}. The tests were carried out to derive constitutive equations capable of describing the flow stress of the material in terms of the strain, strain rate, activation energy, and finally, the deformation temperature. The present experimental results reveal that the temperature range could be divided into two regimes based on the change of the stress exponent and the activation energy with temperature of deformation. The constitutive equations are derived using a regression technique. Good correlation has been obtained between the experimental values of the flow stress and those predicted using the derived constitutive equations.

Keywords: constitutive equations, commercial pure aluminum (1050), high-temperature deformation, regression technique

1. Introduction

Knowledge of the high-temperature deformation behavior of materials is very important for the numerical modeling of many industrial processes. In the modeling of hot working processes by means of numerical techniques, such as finite element and finite difference methods, one of the most important items is, without question, a precise knowledge of the constitutive equations that relate the flow stress of the material to the strain, stain rate, and temperature of deformation. Not only is it important to determine the expected load and power requirements of the process intimately associated with the flow stress of the material being processed, but also the microstructural evolution is highly dependent on accurate calculations of strain rate and temperature fields. The constitutive equations are also significant in hot working processes because they permit extrapolations to the strain and strain rates beyond that of tests.

The deformation behavior of aluminum (Al) and Al alloys at high temperature is characterized by a softening process based on dynamic recovery.[1,2] To model this property, or the relevant softening mechanisms, constitutive equations have been proposed for different situations.[3-6] Some models are based on the concept of internal variables, which take into account the influence of the deformation mechanism and microstructural evolution.[6] For commercial pure Al, Puchi[7] developed a set of constitutive equations capable of describing the flow stress in terms of the strain rate and the deformation temperature. The development has been carried out following the method suggested by Kocks,[8] where the achievement of steady-state conditions of flow stress is considered even at the lowest testing temperature. However, the development of the constitutive equations was based on data obtained at two testing temperatures only, 473 K and 673 K, over a wide range of strain rates (0.095-216 s^{-1}). Wilshire and Palmer[9] have demonstrated recently that the concept of the steady state should be abandoned on the grounds that a steady-state condition is rarely achieved in the case of creep, which is usually carried out at lower strain rates than those encountered in hot working processes.

The objective of the present investigation is to derive new constitutive equations for the deformation of commercial pure Al (1050) at high strain rates and temperatures, which can be used with any numerical technique to model hot working processes. The strain dependence of the flow stress of the material will be included instead of assuming steady-state conditions. For this reason, tensile tests were performed on specimens of commercial pure Al (1050) in the temperature range of 473-673 K and at strain rates ranging from 0.01-0.2 s^{-1}. The empirical constants involved in the new constitutive equations were determined from the experimental data of the flow stress, strain, strain rate, and deformation temperature utilizing a regression technique.

2. Experimental Work

Tensile specimens with a gauge length of 10 mm and a width of 5 mm were cut from a sheet of commercial pure Al (1050) 1 mm in thickness. The specimens were annealed for 4 h at 723 K. Tensile tests were performed using an Instron (UK) tensile testing machine at temperatures of 473, 523, 573, 623, and 673 K at various cross-head speeds corresponding to initial strain rates of 0.01, 0.05, 0.1, and 0.2 s^{-1}. A resistance furnace containing three heating zones controlled by a digital controller was used for all tests. The temperature was allowed to stabilize for a minimum of 10 min at the beginning of each test. The testing temperature was controlled thermostatically within ±3 °C. Load-displacement curves were monitored on a strip chart recorder.

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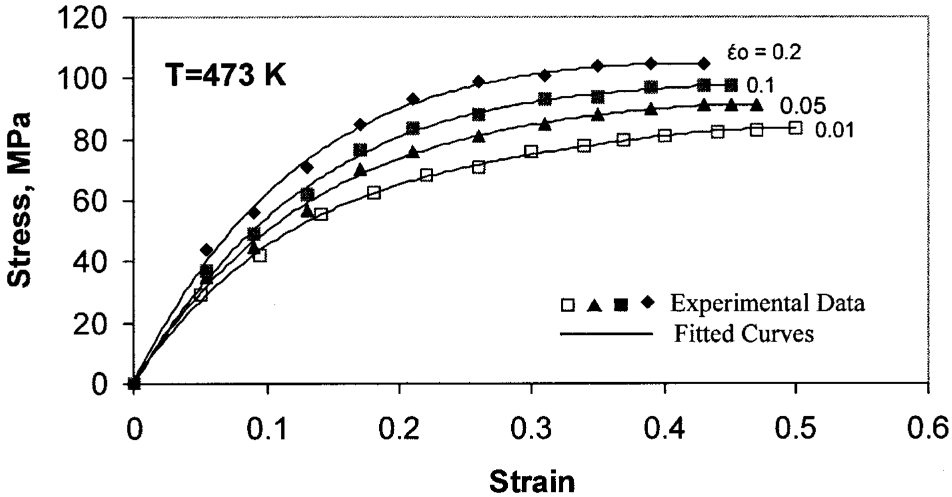

Fig. 1 Experimental data and the fitted stress-strain curve for $T = 473$ K at various initial strain rates

3. Results and Discussion

3.1 True Stress-Strain Curves

The load-displacement charts were used to compute the true stress-strain curves. Figure 1 shows the experimental data and the fitted true stress-strain curve for the case of temperature equal to 473 K and for various initial strain rates. For the sake of comparison, fitted true stress-strain curves for the various testing temperatures and initial strain rates are illustrated in Fig. 2(a-e). Note that the experimental data are omitted for the purpose of clarity. The inspection of these figures reveals the following points. First, at constant testing temperature, the strain hardening increases and the ductility (elongation to fracture) decreases with an increase in the strain rate. Second, as the temperature increases at a constant strain rate, the strain-hardening rate decreases. The steady-state condition was not reached even at the lowest strain rate and the highest testing temperature (i.e., the stress was slightly increasing with the strain).

3.2 Stress Dependence of Strain Rate

The relation between the stress and the strain rate is governed by the following equation[10]:

$$A\sigma^{n} = \dot{\varepsilon}\exp(Q/RT) \qquad \text{(Eq 1)}$$

where A is an empirical material constant, n is the stress exponent, Q is the activation energy (J mol^{-1} K), R is the universal gas constant (R = 8.314 J mol^{-1} K), and finally, T is the absolute temperature. To investigate the stress dependence on the strain rate, the values of the stress rate versus the strain rate at a constant strain of $\varepsilon = 0.4$ are plotted on a log-log scale, as shown in Fig. 3. It is shown that for the temperature range of 473-573 K, three parallel lines are obtained with the stress exponent, in this case n_1, as represented by their slope (≈10), while for the two temperatures 623 and 673 K the two lines are approximately parallel, with a different slope than that of the first three lines (i.e., $n_2 \approx 5$). This indicates that the stress exponent n is a function of the temperature of deformation. Therefore, the temperature range is divided into two regimes. Regime one is for temperatures from 473-573 K, while the second is for temperatures from 573-673 K.

3.3 Apparent Activation Energy

The apparent activation energy, Q, is calculated using the following equation[10]:

$$Q = -R\left[\frac{\partial(\ln\dot{\varepsilon})}{\partial\left(\frac{1}{T}\right)}\right]_{\sigma} \qquad \text{(Eq 2)}$$

As stated above, the temperature range is divided into two regimes. Figure 4 depicts the values of strain rate versus (1000/T) at constant stress for the two temperature regimes. For the first regime, the apparent activation energy is determined to be 98 kJ mol^{-1}, while for the second one the calculated Q value is 142 kJ mol^{-1}. The calculated value of Q in the first instance is less than that for self-diffusion in pure commercial Al ($Q_{s\text{-}d}$ = 142 kJ mol^{-1}), and is due to the contribution of the low temperature activation energy of self-diffusion (Q_L = 115 kJ mol^{-1}) in the vicinity of 0.6 T_m,[11] , where T_m is the absolute melting temperature. It is assumed that in the temperature range 473-673 K the deformation of pure commercial Al would be thermally controlled by the activated climb processes of edge dislocation segments. This assumption is consistent with the well-known fact that under hot working conditions, commercial pure Al (1050) tends to develop a substructure of well-formed subgrains as a consequence of the operation of dynamic recovery, which is the only mechanism of softening that takes place during the deformation process.

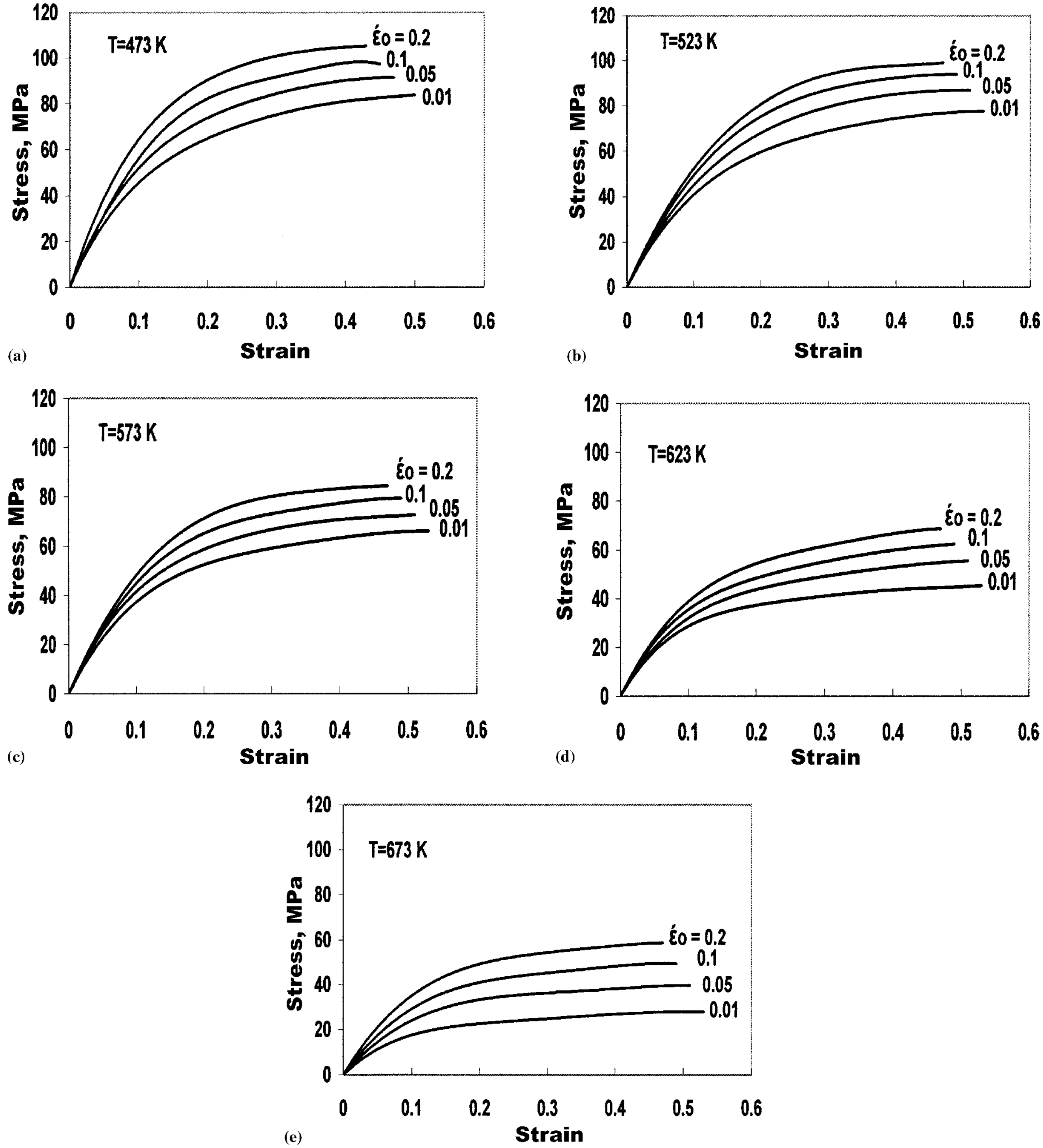

Fig. 2 Fitted true stress-strain curves for pure commercial Al at various temperatures and strain rates

3.4 Deformation Behavior

As stated in the previous section, the deformation of commercial pure Al (1050) in the temperature range 473-673 K is due to the thermally activated climb processes of edge dislocation segments and to the motion of jogged screw dislocations. This behavior is governed by a Dorn equation of the following form,[12]

$$\left(\frac{\sigma}{G}\right)^n = C\left(\frac{\dot{\varepsilon}kT}{bGD}\right) \qquad \text{(Eq 3)}$$

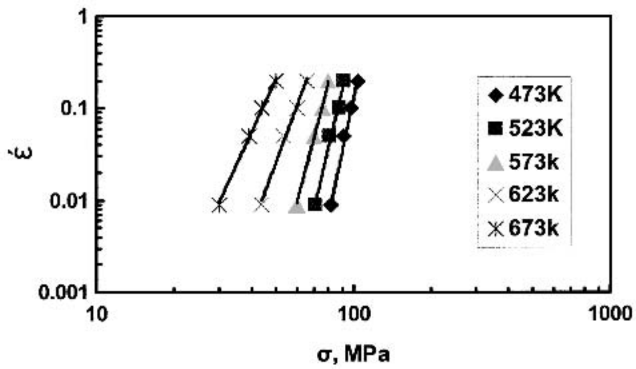

Fig. 3 Stress dependence of the strain rate at $\epsilon = 0.4$ for various temperatures

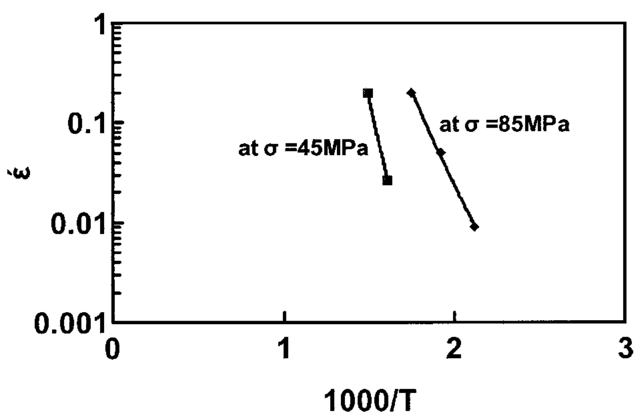

Fig. 4 Temperature dependence of the strain rate at constant stress

where G is the temperature-dependent shear modulus, C is a dimensionless constant, k is Boltzman's constant (1.38×10^{-23} J K^{-1}), b is the magnitude of the Burger vector (2.86×10^{-10} m), and D is the self-diffusion coefficient. For intermediate and high temperature ranges (T_m = 0.4-0.93 K), the following relation is found to be adequate for describing the self-diffusion coefficient D for pure commercial Al (1050)[11]:

$$D = 1.7 \times 10^{-4} \exp(-142/RT) + 6 \times 10^{-7} \exp(-115/RT)\ m^2/s \quad \text{(Eq 4)}$$

The temperature-dependent shear modulus for pure commercial Al is given by the following expression, which was formulated based on reported experimental data[7]:

$$G = (29.5733 - 0.014T) \times 10^3\ MPa \quad \text{(Eq 5)}$$

Figure 5 shows the relationship between $\dot{\varepsilon}kT/bGD$ and σ/G for different temperatures and strain rates. The values of the stress exponent, n, change from ≈10 at 473 K to ≈5 at 673 K. This correlation of data is similar to that presented by McQueen[13] for pure Al.

4. Constitutive Equation

In the literature, the development of the constitutive equations is usually based on three popular equations: the power law for low stresses; the exponential law for high stresses; and the more general hyperpolic sine relationship quoted by Sellars and Tegart[14] for the full range of stresses. These relations have been used to describe the temperature and strain rate

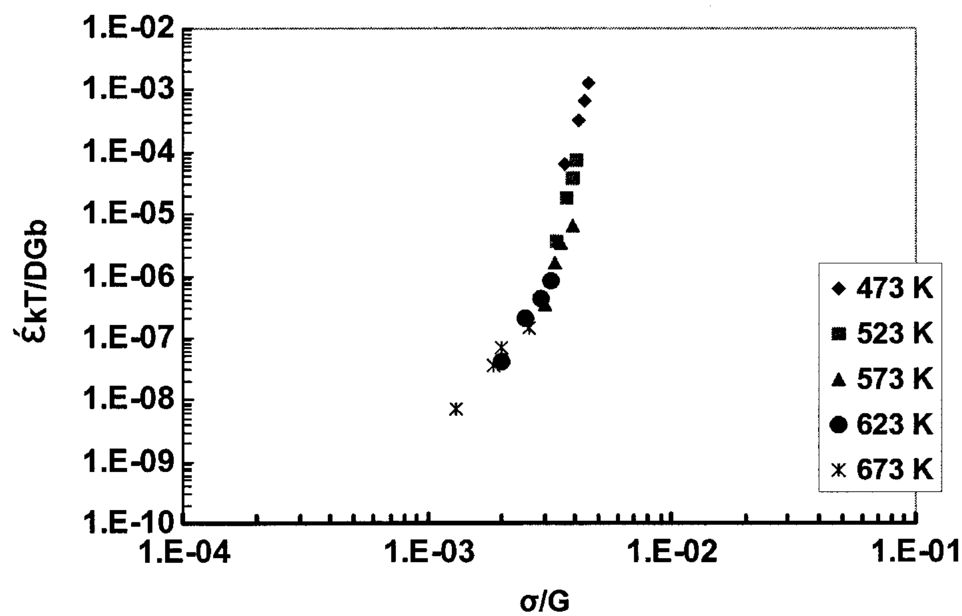

Fig. 5 Relation between normalized strain rate and normalized stress

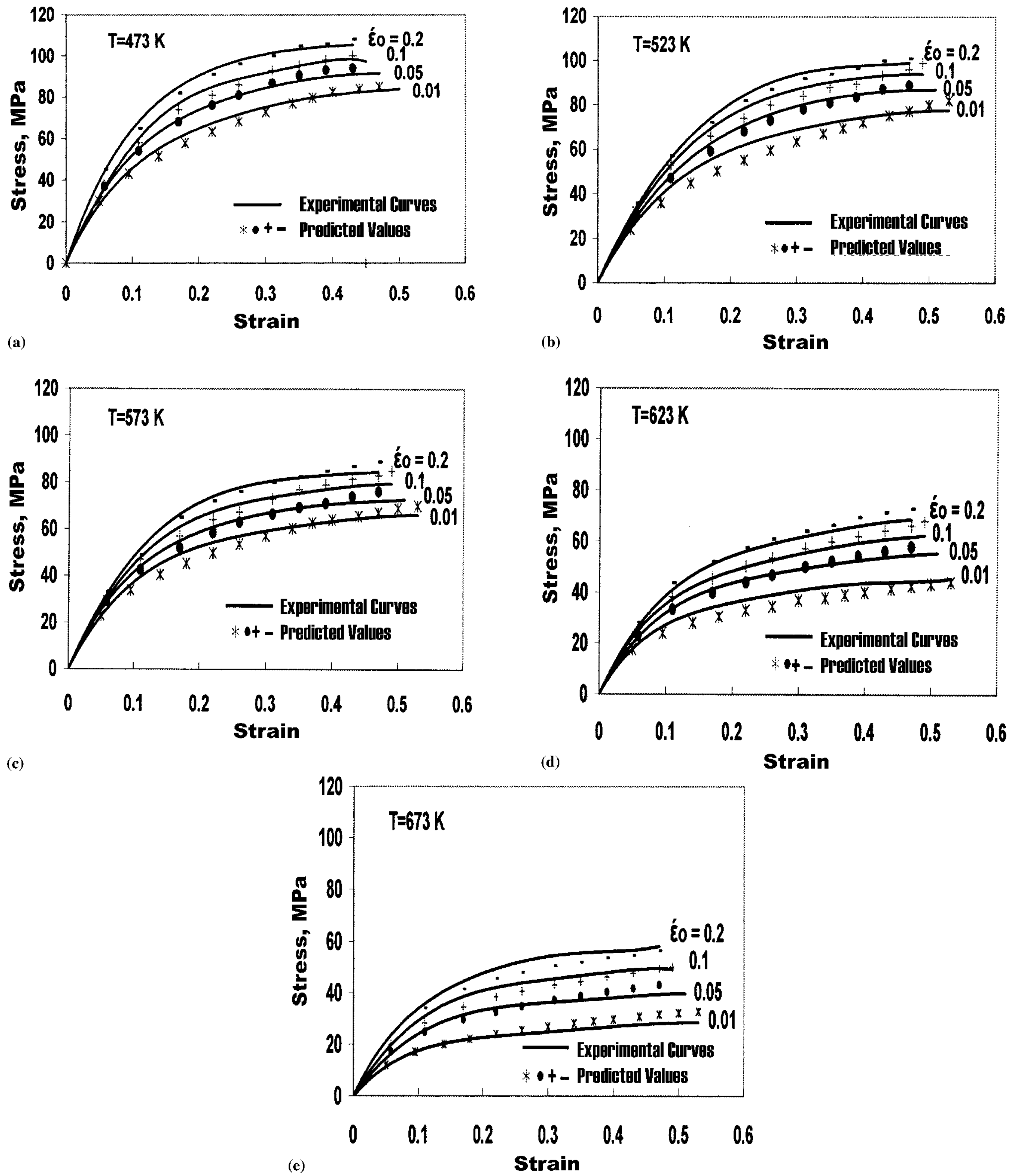

Fig. 6 Comparison between the predicted values of the flow stress and the experimental curves

dependence of the steady-state stress during the high-temperature deformation of many different materials (see, for example, Ref. 7 and 14-19).

As stated above, the concept of a steady-state condition is questionable since the steady-state response is rarely achieved. In the present analysis, therefore, a trial was performed to develop the constitutive equation based on the regression technique, using a regression equation of the following form:

$$\sigma = p\varepsilon^{q} T^{r} Z^{S} \quad \text{(Eq 6)}$$

where

$$Z = \dot{\varepsilon}\exp(Q/RT) \quad \text{(Eq 7)}$$

is the Zenner-Hollman parameter and p, q, r, and s are empirical material constants to be determined. The Zenner-Hollman parameter is beneficial in hot working processes since it embraces the three control variables: $\dot{\varepsilon}$, T, and Q.

The corresponding true strain rate values are computed from those of the initial strain rate through the relation $\dot{\varepsilon} = \dot{\varepsilon} l_o / l$ (where l_o and l are the initial and instantaneous lengths of specimens, respectively). Once again, the temperature range is divided into two regimes, and the same form of the regression is used in each of them. A statistical software package (SPSS, version 10, SPSS, Chicago, IL) has been used.[20] For the first regime, the following equation was found with correlation coefficient of $r^2 = 0.941$ (where the measure r^2 shows the proportion of the variability in the data explained by the derived equation):

$$\sigma = 2.729 \times 10^{-2}\, \varepsilon^{0.475}\, T^{1.042} Z^{0.0995}\ \text{MPa} \quad \text{(Eq 8)}$$

While for the second one, the following equation was obtained with $r^2 = 0.938$

$$\sigma = 2.0511 \times 10^{-4}\, \varepsilon^{0.429} T^{1.277}\, Z^{0.195}\ \text{MPa} \quad \text{(Eq 9)}$$

It is apparent from Eq 8 and 9 that the flow stress σ is increasing as the temperature increases. This is true, but the effect of temperature is also included in the Zenner-Hollman parameter Z in exponential form (Eq 7). Thus, the decrease in σ due to the temperature increase in the parameter Z is actually more pronounced than that due to the power dependence of the temperature.

The confidence and reliability of the derived constitutive equations is confirmed by the following two points: the higher values of r^2 in each case and the values of the strain rate sensitivity, as represented by the exponent of Z in the regression equations, are $m_1 = 0.0995$ and $m_2 = 0.195$, respectively, for the first and the second regimes. These values are in good agreement with the values of stress exponents deduced from the Dorn equation ($m_1 = 1/n_1 \approx 0.1$, and $m_2 = 1/n_2 \approx 0.2$).

Figure 6(a-e) shows the comparison between the predicted and the experimental values for flow stress versus strain for different temperatures and strain rates. It can be seen that the agreement is more than satisfactory.

Finally, it should be emphasized that the constitutive equations derived herein are completely different from those found in the literature, since they contain the strain term. Therefore, they could be used to model the transient and steady state deformation conditions in any metal-forming process such as hot rolling, forging, and extrusion processes. Also, they could be easily incorporated into any finite element package. Once again, the previously developed constitutive equations found in the literature were based on the steady-state conditions.

5. Conclusions

The high-temperature deformation behavior of commercial pure aluminum (1050) was investigated by performing tensile tests in the temperature range 473-673 K and at initial strain rates between 0.01 and 0.2 s^{-1}. The analysis of the experimental results revealed that the stress exponent and the activation energy vary with the temperature of deformation. The temperature range is divided into the following two regimes: the first is from 473-573 K; while the second is from 573-673 K.

New constitutive equations have been derived that include the strain dependence of the flow stress as well as the strain rate, temperature, and activation energy. The empirical constants involved in these constitutive equations were determined from the experimental data of flow stress, strain, strain rate, and deformation temperature by utilizing a regression technique. Good correlation has been obtained between the experimental values of the flow stress and those predicted using the derived constitutive equations. Therefore, these equations can be used confidently in conjunction with any numerical algorithm based on the finite difference method or finite element codes to simulate the hot working processes carried out on this material.

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