DEFORMATION OF HIGH-TEMPERATURE SUPERCONDUCTORS

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INTRODUCTION

Of the many families of high-temperature superconductor, only the properties of those discovered prior to 1989 — Y–Ba–Cu–O, Tl–Ba(Sr)–Ca–Cu–O, and Bi(Pb)–Sr–Ca–Cu–O — have been studied extensively.1 Deformation tests have been performed on YBa2Cu3Ox (Y–123), YBa2Cu4Ox (Y–124), TlBa2Ca2Cu3Ox (Tl–1223), Bi2Sr2CuOx (Bi–2201), Bi2Sr2CaCu2Ox (Bi–2212), and (Bi,Pb)2Sr2Ca2Cu3Ox (Bi–2223).2–13 The tests have revealed that plasticity is generally limited in these compounds and that the rate-controlling diffusional kinetics for creep are very slow. Nevertheless, hot forming has proved to be quite successful for fabrication of bulk high-temperature superconductors, so long as deformation rates are low or large hydrostatic stresses are applied.13–20

Steady-state creep data have proved to be useful in designing optimal heat treatments for superconductors and in support of more-fundamental diffusion experiments.21,22 The high-temperature superconductors are highly complex oxides, and it is a challenge to understand their deformation responses. In this paper, results of interest and operant creep mechanisms will be reviewed.

EXPERIMENTS AND MATERIALS

Most of the data cited are from our own work. Details of specimen preparation have been published.3,4,6,7,10–12 Specimens were about 3 x 3 x 5 mm. The Y–123 specimens were nearly fully dense and phase pure. The Tl–1223 specimens were 73–86% dense and ~90% phase pure. The Bi–2201, 2212, and 2223 specimens were 92–99% dense; the Bi–2201 and 2212 were nearly phase pure and the 2223 was ~90% pure.

The specimens were compressed between Al2O3 platens at nearly constant strain rate in an Instron machine fitted with a high-temperature furnace or at constant load.4,6,12 In some cases, Ag or Pt foil was used as a diffusion barrier. Total strain was generally limited to ~10% and no appreciable specimen densification occurred during testing. Strain rates...
were based on initial sample length. Several deformed specimens were examined by scanning and transmission electron microscopy (SEM and TEM).

RESULTS AND DISCUSSION

All of the high-temperature superconductors have similar layered perovskite crystal structures (Fig. 1).\(^1\) Cu–O planes, which are responsible for the superconductivity, are common to all. As would be expected, creep properties of these compounds are generally similar. Results for Y–123 are by far the most extensive. These will be presented first and the results from the others will then be compared.

Creep of YBa\(_2\)Cu\(_3\)O\(_x\)

Y–123 is a highly oxidized compound that is stable over only a rather limited range of temperature (T) and oxygen pressure (P\(_{O2}\))\(^2\). Reliable deformation tests have been performed from 750 to 980°C for specimens of average grain size (d) between 7 and 70 \(\mu\)m. The P\(_{O2}\) range was 10\(^3\)–10\(^5\) Pa.\(^2\)-5,12,25,26 Steady state strain rate \(\dot{\varepsilon}\) was fit to a phenomenological expression

\[
\dot{\varepsilon} = A d^{-p} \sigma^n P_{O2}^m \exp\left(-\frac{Q}{RT}\right),
\]

where A is a constant, p, n, and m are exponents, \(\sigma\) is the steady–state stress, Q is the activation energy, and R is the gas constant.\(^2\)

A range of values for the various parameters in Eq. 1 have been reported in the literature.\(^2\)-4,9,12,26 For some time, the principal confusion, for which we were responsible, was the effect of temperature and P\(_{O2}\) on Q. We reported initially that Q was a function of P\(_{O2}\).\(^3\),4 Recent experiments have resolved apparent discrepancies.\(^12\) For Y–123, with T > 900°C and \(\sigma < 10\) MPa,

\[
\dot{\varepsilon} = A d^{-2.7 \pm 0.6} \sigma^{1.0 \pm 0.1} P_{O2}^{-0.5 \pm 0.2} \exp\left(-1100 \pm 100\right) \text{kJ/mole}/\text{RT}. \quad (2)
\]

For T \(\leq\) 880°C, the Q dropped to 675 ± 70 kJ/mole. Q depended only on temperature. The exponents n and m were independent of temperature. The value for p exhibited rather large scatter and has not been investigated thoroughly as a function of temperature. For Y–123 with submicron–sized grains, superplastic flow with an n value of 2.0 have been observed.\(^8\),9

The measured creep parameters indicate a diffusional creep mechanism. No significant dislocation activity was observed in TEM and no change of grain shape was observed by SEM. Therefore, grain–boundary sliding (GBS) accommodated by diffusion was inferred to be the deformation mechanism. The Ashby–Verrall model for GBS in a compound can be expressed as

\[
\dot{\varepsilon} = A'\left(\sigma \Omega_{\text{mol}}/kT\right) d^{-2} D_{\text{mol}},
\]

where the threshold stress has been assumed to be negligible, \(A' = 98\), \(\Omega_{\text{mol}}\) is the molecular volume, and \(D_{\text{mol}}\) is the effective molecular diffusion coefficient, which takes into account diffusion in the bulk and along grain boundaries.\(^12,28\)

Equation 3 can be used to calculate diffusion coefficients directly.\(^12\) Results of these calculations can be compared with measured tracer diffusivities.\(^22\) We take creep data from Ref. 4 at the highest temperatures, for which lattice diffusion should dominate, and lattice parameter data from Ref. 1: d = 30 \(\mu\)m, T = 950°C, \(\sigma = 1\) MPa, \(\dot{\varepsilon} = 10^{-6} \text{s}^{-1}\), and