Strain-energy relaxation mechanisms in geological materials

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Isothermal mechanical spectroscopy of geological materials is beginning to elucidate the microscopic processes responsible for their high-temperature viscoelastic relaxation. Grain-boundary sliding is implicated in the results of recent studies of fine-grained synthetic polycrystals of the upper-mantle mineral olivine and other ceramic materials, but is not adequately described by the classic theory. Indications of a major role for dislocation relaxation require systematic experimental investigation.

1. Introduction

Most of the pioneering experimental work on internal friction peaks in metals at low temperatures was undertaken with resonant (i. e. pendulum) techniques. More recently, there has been growing recognition of the superiority of mechanical spectroscopy methods in which sub-resonant forced oscillations probe the relaxation spectrum under isothermal high-temperature conditions that afford the benefit of a stable microstructure. Mechanical spectroscopy is particularly well suited to investigation of the high-temperature background — the monotonic variation of Q^{-1} with frequency and temperature that typically dominates the dissipation at high temperature and low frequency. Complementary microcreep tests are also being increasingly widely used to distinguish between recoverable (anelastic) and permanent (viscous) components of the strain. Systematic application of these methods to geological (and related ceramic) materials is providing rigorous tests of classic theoretical models that provide plausible, though highly idealised, descriptions of the viscoelastic relaxation associated with grain-boundary sliding [1, 2] and dislocation motion [3,4].

2. Classic theory of grain-boundary sliding

With increasing temperature and/or timescale it is envisaged that relative tangential displacement of neighbouring grains is facilitated by the presence of a thin boundary region of low viscosity. The resulting mismatch across the boundary is accommodated either by elastic distortion of the grains or by diffusional transport of matter along the boundary — giving rise to anelastic or viscous deformation, respectively. Expressing the boundary topography for a 2-D array of close-packed hexagonal grains and the distribution of normal stress across the slipped boundary as Fourier series truncated after $N = 100$ terms, Raj and Ashby [1] derived an expression for the equilibrium elastically accommodated sliding distance U, and hence a substantial anelastic relaxation strength Δ (Fig. 1a). With a unique value for the anelastic relaxation time, the behaviour is that of the standard anelastic solid with its Debye dissipation peak. However, the infinite sum in the denominator of the expression for U actually fails to converge [5, 6]. The inferred relaxation strength is a function of the number of retained terms (Fig. 1a) — decreasing towards zero as N tends to infinity. It thus seems possible that elastically accommodated grain-boundary sliding might be inhibited by sufficiently tight grain-edge intersections, associated with large values of N.

As regards diffusional accommodation, Raj [2] determined the duration τ_d of the transient required to adjust the normal stress distribution from that prevailing on completion of elastically accommodated sliding to that required for steady-state diffusional creep. The transient creep rate is enhanced relative to the corresponding steady-state diffusional creep rate by a numerical factor that varies approximately as $(t/\tau_d)^{-1/2}$, which integrates to a creep function of the Andrade form [7]. This creep function involves an infinitely wide distribution of anelastic relaxation times resulting in a broad absorption band within which the dissipation varies with oscillation period T_o and grain size d as $Q^{-1} \sim T_o^{1/2} d^{-s}$ with $1 < s < 3/2$ [5, 7].

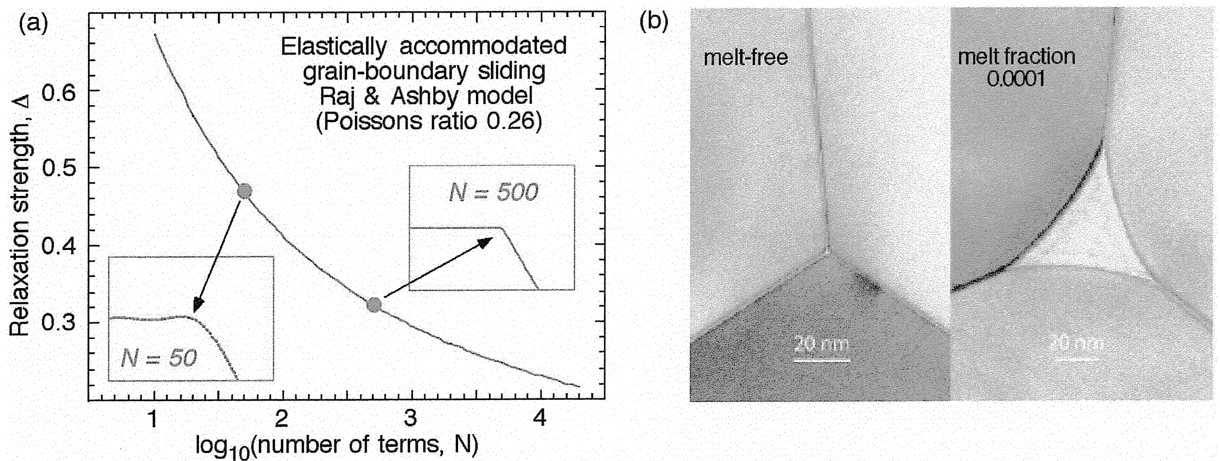

Fig. 1. (a) The effect of truncation after N terms of the Fourier series representing grain-boundary topography [1] upon the relaxation strength for elastically accommodated sliding [6]. (b) Contrasting grain-edge triple-junctions for melt-free and melt-bearing olivine [5].

3. Microstructures and viscoelastic behaviour of fine-grained polycrystalline olivine

The contrasting grain-edge microstructures of genuinely melt-free and basaltic melt-bearing olivine polycrystals are shown in Fig. 1b. The non-wetting melt phase forms triple-junction tubules. For specimens sufficiently pure to avoid partial melting at the highest testing temperatures (1200-1300°C), the edges of adjacent olivine grains are tightly interlocking at the 2 nm level. These microstructural differences are reflected in qualitatively different viscoelastic behaviour. The genuinely melt-free specimens display only a monotonically frequency and temperature-dependent background dissipation (Fig. 2a) that is mildly grain-size-sensitive.

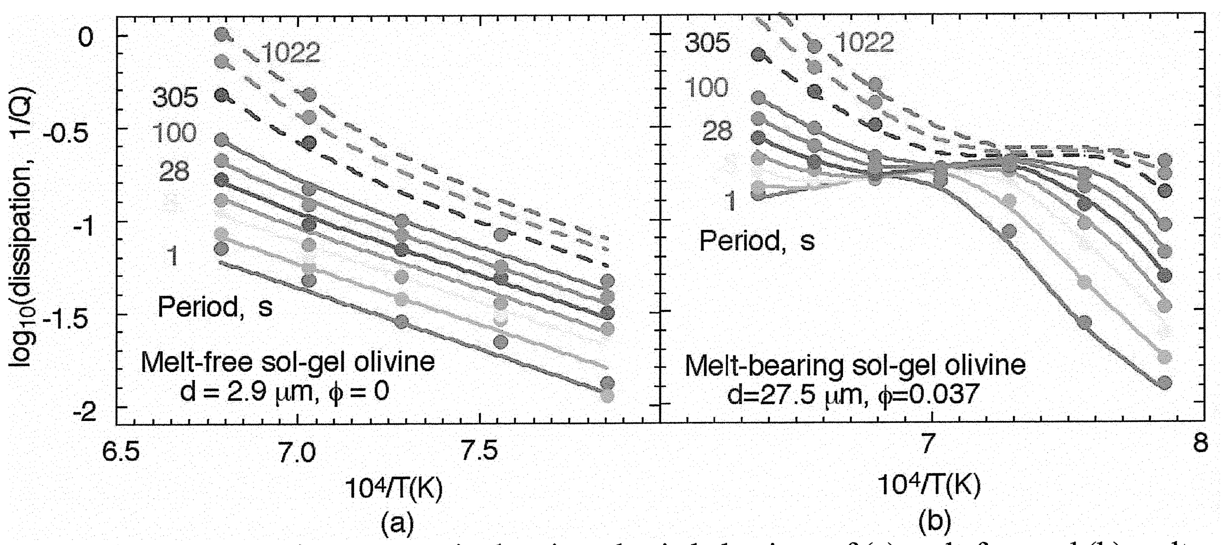

Fig. 2. Contrasting patterns in the viscoelastic behaviour of (a) melt-free and (b) melt-bearing olivine polycrystals [8].

For melt-bearing specimens a broad dissipation peak, whose height scales with melt fraction ϕ, is superimposed upon a melt-enhanced background (Fig. 2b). The presence or absence of a Q^{-1} peak is correlated with the grain-edge microstructures: elastically accommodated sliding manifest in a peak being inhibited by tight grain-edge intersections in the melt-free materials, but apparently facilitated by the rounded grain edges in the melt-bearing specimens. Grain-boundary sliding with diffusional accommodation, responsible for the background, is evidently able to proceed in isolation or in parallel with elastically accommodated sliding.

4. Dislocation relaxation mechanisms

In the simple vibrating string model of dislocation relaxation, the displacement $u(t)$ of a dislocation segment of length L between pinning points is determined by the balance between the force σb per unit length of dislocation line exerted by shear stress $\sigma(t)$, the line tension $T_l = (1/2)Gb^2$ and a drag force Bdu/dt. For a population of such segments of dislocation density Λ, the behaviour is that of the standard anelastic solid with relaxation time $\tau = (1/6)\Lambda L^2$ and strength $\Delta = (1/6)BL^2/Gb^2$ [4]. A distribution $p(L) \sim L^{2\alpha-4}$ of segment lengths is required for an absorption band with $Q^{-1} \sim T_o^{\alpha}$, with $0 < \alpha < 1$ [9].

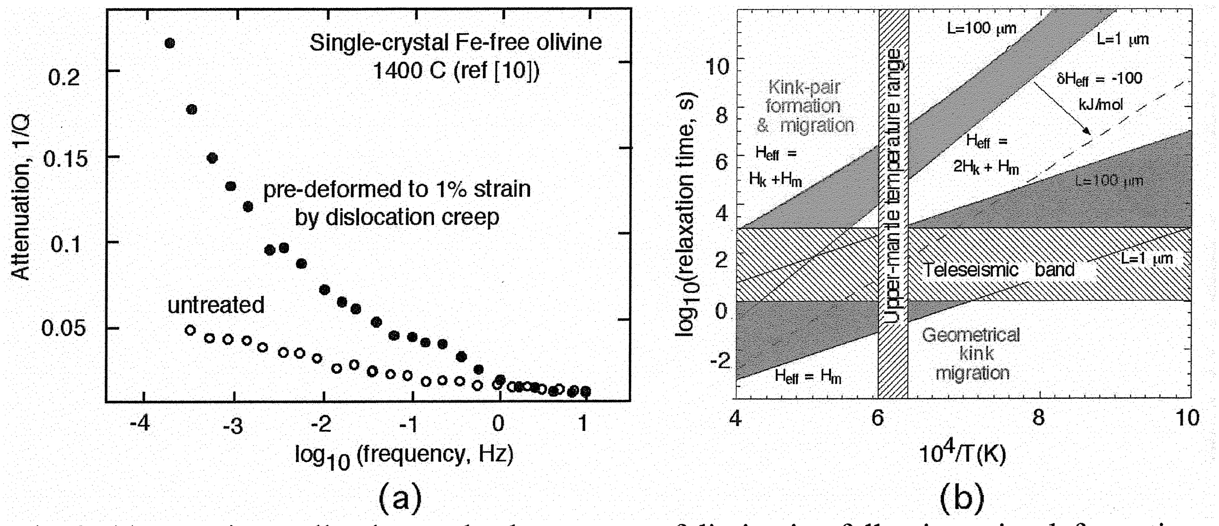

Fig. 3. (a) Experimentally observed enhancement of dissipation following prior deformation by dislocation creep [10]. (b) Relaxation times for kink migration from Seeger s theory [3].

For silicate minerals with high Peierls stress it is likely that the stress-induced migration of dislocations is actually achieved by the migration of (pre-existing) geometrical kinks and/or the formation and separation of kink pairs. Calculations based on theory [3] suggest time scales for geometrical kink migration within the seismic band for temperatures of 1200-1400 °C (Fig. 3b). It follows that dislocation relaxation may explain the enhanced dissipation in pre-deformed specimens tested in the laboratory (Fig. 3a, [10]) and also contribute to seismic-wave attenuation in the Earth s mantle [11].

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