A high-temperature torsion apparatus for the high-resolution characterization of internal friction and creep in refractory metals and ceramics: Application to the seismic-frequency, dynamic response of Earth's upper mantle

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The design and performance of a compact apparatus for the characterization of internal friction in simple shear at elevated temperature ($\leqslant 1400\,°C$) and low frequencies ($\leqslant 1$ Hz) are described. High-temperature components are fabricated from a refractory molybdenum alloy that is straightforwardly machined. The apparatus has demonstrated, at high temperature, a torque resolution of 2×10^{-5} N m and an angular displacement resolution of 4×10^{-6} rad; for the specimen size we employ, these limits provide a shear stress and strain resolution of 2 kPa and 5×10^{-7}, respectively. The apparatus, while applicable to dynamic and static mechanical analyses of any engineering material, was developed for the characterization of internal friction (attenuation) in synthetic silicate aggregates representative of Earth's upper mantle; we discuss the constraints inherent in the required tests, as they affect apparatus design (including materials selection) and experimental protocol. Static and dynamic data at 1250 °C for a polycrystalline aggregate of ferromagnesian olivine of controlled, uniform ($\sim$3 μm) grain size are presented and discussed. © *1998 American Institute of Physics.* [S0034-6748(98)00602-9]

I. INTRODUCTION

During creep deformation (constant applied differential stress at an elevated, constant temperature), most polycrystalline materials initially display a decelerating transient in the strain rate that decays to a ''steady-state'' regime of constant, or near-constant strain rate. This initial transient response is often ignored in the literature despite the fact that in many loading situations (e.g., vibrations) the transient regime may dominate the mechanical response of a material.

One of the simplest approaches to studying transient creep is to apply a constant stress to a material and observe how the material responds over time. Unfortunately, it is often difficult to accurately measure the high strain rates–characteristic of transient creep–that occur instantaneously upon the application of the load. A far better method to study transient creep is to apply cyclical (e.g., sinusoidal) loads at a range of frequencies corresponding to the range of times characteristic of the transient, thereby effectively keeping the sample in the transient regime indefinitely. The instrument described herein (henceforth called the ''torsion apparatus'') was created to perform such tests at temperatures of up to 1400 °C and with stress and strain resolution of 2 kPa and 5×10^{-7}, respectively.[1]

This specific torsion apparatus was designed and constructed to investigate the dynamical response of materials that are representative of the upper mantle of Earth—that portion of the planet at a depth (e.g., under ocean basins) of 10–400 km. Seismic studies reveal a complex dynamic mechanical behavior in the upper mantle, including a zone at a depth of 50–150 km of pronounced attenuation of seismic waves and a slowing of their velocities, the so-called high-attenuation, low-velocity zone (HALVZ or LVZ), that defies explanation by first-order effects.[2,3] Partial melting of the mantle rock, which in the solid state consists principally of iron-magnesium orthosilicate (olivine, $[\mathrm{Mg,Fe}]_2\mathrm{SiO}_4$, $\sim$60 vol %), iron–magnesium and iron–magnesium–calcium metasilicates (pyroxenes $[\mathrm{Mg,Fe}]\mathrm{SiO}_3$ and $\mathrm{Ca}[\mathrm{Mg,Fe}]\mathrm{Si}_2\mathrm{O}_6$, $\sim$20 vol %) and alkali and alkaline earth aluminosilicates (e.g., feldspars, $[\mathrm{Ca}_x\mathrm{Na}_{1-x}][\mathrm{Al}_{1+x}\mathrm{Si}_{3-x}]\mathrm{O}_8$ $\sim$17 vol %), is often invoked to explain this anomaly. Experimental studies on upper mantle materials suggest that partial melting will produce a quasiequilibrium solid–liquid microstructure in which the melt phase will be restricted to the three-grain (''triple'') junctions, leaving the two-grain interfaces (i.e., grain boundaries) melt-free (cf. Ref. 4). This structure allows for a highly efficient, gravity-driven separation of the melt phase and crystalline residuum (i.e., melt migration) such that steady-state volumetric melt fractions during mantle melting remain of order 1 vol %.[5] The effect of such a small melt fraction, both theoretically considered and experimentally measured, on the steady-state creep properties is modest.[4,6] Interfacial thermodynamics, however, predicts that this equilibrium melt phase will migrate in response to a gradient in the hydrostatic component of the total stress, producing a notable, time-dependent (transient) dilatational strain, and so effect a distinct seismic attenuation (internal friction) signature. The veracity of this hypothesis was probed experimentally for pyroxene- and olivine-liquid ag-

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