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Experimental and theoretical approaches to grain boundary premelting: a possible origin of asthenosphere

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Enhancement of grain boundary disorder near the melting temperature, or premelting, has been known for ice, but not for a rock. Recently, possible occurrence of premelting in the upper mantle has become a matter of concern, because it causes a solid-state weakening of rock and enables an explanation of the seismic low velocity zones and weak asthenosphere without invoking melt. It overcomes a difficulty to explain seismological and geochemical observations in a consistent manner. There exist experimental and seismological evidences for the occurrence of premelting. Using a binary eutectic polycrystalline system as a rock analogue, Yamauchi and Takei (2016, JGR) measured sample viscoelasticity over a broad frequency range from purely elastic, through anelastic, to viscous, and demonstrated a significant enhancement of anelastic relaxation and viscous deformation from just below the eutectic temperature, where melt does not exist. Also, using the thermal and seismic models of the Pacific mantle, Priestley and McKenzie (2013, EPSL) demonstrated a steep reduction of shear wave velocity from just below the peridotite solidus, which is explained well by the mechanical model of rock based on the experimental data of Yamauchi and Takei (2016) (Takei, 2017, Ann. Rev.).

We will report our experimental and theoretical approaches to understanding the underlying physics and mechanical consequences of premelting. Important mechanical consequences of premelting are a significant enhancement of grain boundary sliding and grain boundary diffusion. Dissipation spectrum of a polycrystalline material by grain boundary sliding usually has a universal form, which is expressed as $Q^{-1}(f/f_M)$ with Maxwell frequency f_M. Onset of premelting can be characterized by a breakdown of this scaling law: dissipation at high normalized frequencies f/f_M increases significantly, causing a large and steep reduction of seismic velocity. Onset of premelting is also characterized by an increase in the activation energy of grain boundary diffusivity. These observations indicate a change in grain boundary structure (enhanced disorder). In the area of material sciences, theoretical model based on the statistical physics has recently been developed to treat grain boundary disorder at the atomic scale and connect it to the dynamic properties. Application of this physical model is, so far, limited to simple pure systems. Instead, we applied a thermodynamic model of grain boundary (Tang et al., 2006, Phys. Rev. Lett.) to our experimental results. Although the model includes some phenomenological parameters, it clarifies a mutual relationship of premelting with partial melting, grain boundary adsorption (segregation), and equilibrium dihedral angle of melt.