STRUCTURE AND RHEOLOGY OF PARTIALLY MOLTEN AMMONIA-WATER ICES ;

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The physical properties of partially molten planetary materials, including permeability and rheology, are fundamentally dependent on the grain-scale distribution of the melt phase [1,2]. The results of high-pressure creep experiments on fine-grained partially molten ammonia-water ices reported in [3] have been analyzed in the context of recent observations of the wetting characteristics of the melt in two-phase ammonia-water ices. These creep experiments explored the effects of temperature T, strain rate $\dot{\varepsilon}$, melt fraction ϕ, and grain size on creep strength. Experiments were conducted in a gas-medium apparatus designed for cryogenic use under the following conditions: $3.5\times10^{-6} < \dot{\varepsilon} < 3.5\times10^{-4}$ s^{-1}, $160 < T < 220$ K, and confining pressure P_c=50 MPa. Samples were prepared containing 1, 5 or 8 wt% ammonia, yielding calculated melt fractions, respectively, of 3-4, 15-20, and 24-32 vol% from the peritectic temperature T_P=176 K to T=220 K. Partial melting of samples containing 1 wt% ammonia resulted in less than a factor of 2 decrease in strength over the entire experimental temperature range. Samples containing 5 and 8 wt% ammonia, however, exhibit a more dramatic loss of strength -- up to a factor of 5 -- at temperatures just above the peritectic temperature. Scanning electron microscope (SEM) micrographs of samples equilibrated at T=185 K for 24 h at a confining pressure P_c=1 atm reveal that at low melt fractions (e.g., 3 vol%) melt is confined to triple junctions, that is, grain faces remain melt-free. In contrast, at higher melt fractions, ammonia-water melt completely surrounds Ice I grains, so that the rheologically critical melt fraction ϕ_c is exceeded, as shown in Figure 1.

The presence of melt in a polycrystalline aggregate can have a profound effect on rheology, both in the dislocation and in the diffusion creep regimes [4,5]. Melt increases the rate of dislocation creep due to the stress enhancement caused by a decrease in load-bearing area. Likewise, melt increases the rate of diffusional creep due not only to an enhancement in stress but also to the presence of high diffusivity melt-filled pathways [6]. Thus, the distribution of the melt phase, often characterized by a dihedral or wetting angle θ, governs the creep strength of a partially molten aggregate. For $0° < \theta < 60°$, at low melt fractions, melt forms an interconnected network along three-grain and through four-grain junctions; at high melt fractions, the grains become completely surrounded by melt [1].

Previous microstructural analysis of ammonia-water ices deformed at high pressure has relied on replication of the outer sample surface by the indium jackets used to seal the samples [7]. This technique, however, does not provide adequate spatial resolution to measure the dihedral angle. A cryogenic temperature stage was developed for an environmental scanning electron microscope (ESEM) in the High Resolution Microscopy Center at the University of Minnesota that allows *in situ* microstructural characterization of ammonia-water ice samples. This cryosystem consists of a copper sample stage coupled to a self-pressurized liquid nitrogen (LN_2) dewar; subsolidus sample temperatures (<T=176 K) are maintained by circulating LN_2 through the sample stage at a controlled rate. The system provides stable temperature control in the range 100 K <T< 273 K. The ESEM permits samples to be analyzed at much higher chamber pressures than is possible in a conventional SEM (i.e. ~10^{-6} Torr vs. ~10^{-5} Torr). In addition, sputter-coating of a high-conductivity material on the ice surface is not necessary in the ESEM, as would be required in a conventional SEM. The higher chamber pressures in the ESEM, combined with the lower temperature environment, reduces the rate of sample sublimation to a negligible level. Condensation on the sample surface is minimized through the use of a dry imaging gas, such as N_2, instead of water vapor; special sample exchange techniques are also used to minimize condensation.

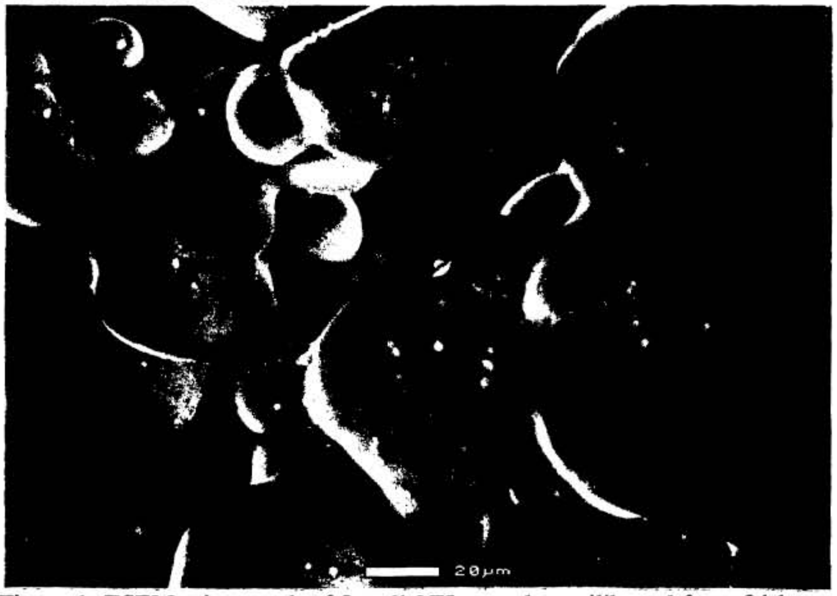

Figure 1- ESEM micrograph of 8 wt% NH_3 sample equilibrated for t=24 h at 1 atm pressure, T=185 K. Calculated melt fraction ϕ=~0.24. Note that Ice I grains are completely separated by melt.

With this newly developed capability, SEM observations have been made in the ammonia-water system. At T=185 K for the composition X_{NH3}=0.01, the dihedral angle is quite small, with $\theta \leq 20°$. Hence, in the ammonia-water system, just above the peritectic temperature and for low melt fractions, melt forms a three-dimensional, interconnected network. At higher melt fractions, as in the X_{NH3}=0.05 and 0.08 cases, Ice I grains are completely separated by melt, as shown in Figure 1. These SEM observations, coupled with the results of the creep experiments performed at hypersolidus temperatures for the samples with 5 and 8 wt% ammonia demonstrate that ϕ_c must be substantially less than 15 vol%. Consequently, partially molten ammonia-water ice near the surface and further within icy planetary bodies will undergo a dramatic loss of strength at relatively small melt fractions (i.e., at relatively water-rich compositions). These results also imply that the strength of partially molten ammonia-water ices will be critically dependent on the permeability, which will control the amount of melt retained in the ice body [8,9].

References

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