THE WEAKENING OR STRENGTHENING OF WATER ICE IN RESPONSE TO CYCLIC LOADING.

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Summary: Icy satellites experience billions of cycles of tidal stress over their histories. Cyclic loading can increase microcrack density and reduce the brittle yield stress of materials in a process known as fatigue[1]. If fatigue occurs on icy satellites it could lower the brittle yield stress near the surface, possibly facilitating increased geologic activity by allowing stresses from solid-state convection and tides to more easily deform the lithosphere [2].

We performed fatigue tests on water ice to measure the rate of weakening at various stress and temperature conditions. We find that ice at 233 K and 198 K does not weaken due to cyclic loading. Samples that experienced up to 80,000 cycles ultimately failed at similar if not higher stresses than samples that experienced no cyclic loading. Although fatigue did not occur for our experimental conditions, lower temperatures on icy satellites and the presence of chemically reactive components may be more likely to promote fatigue.

Background: During fatigue, damage accumulates and microcracks grow under the action of cyclic loads [3]. The stress intensity on microcrack is a function of both the tensile stress, σ_{11}, and crack length, a, where, $K_I = \sigma_{11}\sqrt{\pi a/2}$ [4]. Fracture occurs when the stress intensity reaches the critical value called the fracture toughness[5], K_{Ic}. The fracture toughness of ice ranges from 80 – 150 kPa m$^{1/2}$ and is weakly sensitive to strain rate and temperature [6,7,8]. For fatigue to occur, microcracks must grow at stress intensities below the fracture toughness. Two mechanisms that can contribute to fatigue crack growth are fatigue corrosion and reverse plastic slip [9]. Fatigue corrosion (stress corrosion) involves the weakening of molecular bonds near the crack tip by reactive impurities[10]. Reverse plastic slip promotes crack growth during dislocation propagation from the crack tip[9]. The stress intensity strongly controls fatigue crack growth rates, however changes in microstructure, temperature, and chemical environment also have a dramatic influence [1].

A common method for measuring fatigue is the S-N failure test [1]. Samples are subjected to a cyclic load of a set magnitude and the number of cycles to failure is measured. Many materials exhibit a fatigue threshold, where below a certain stress magnitude materials can endure a practically unlimited number of cycles without brittle failure [11].

S-N failure tests of sea ice performed in situ [12,13], as well as laboratory experiments on fresh water ice [14], found that ice weakens under cyclic loading and that ice may have a fatigue threshold of approximately 50% of the static failure stress[13]. However, other laboratory investigations found that ice does not weaken and cyclic loading may even increase the brittle failure stress [15,16,17]. Plastic deformation during cyclic loading was suggested to cause crack tip blunting, thereby strengthening the ice[15]. All these studies were performed at temperatures $T = 253 - 268$ K, much greater than near surface temperatures on icy satellites where plastic deformation is not significant.

Experiments: We perform fatigue experiments on polycrystalline fresh water ice at $T = 193 - 243$ K and a loading frequency of 1 Hz. Low temperatures and high strain rates, relative other ice fatigue studies, were chosen to minimize the effect of plastic deformation and approach the brittle conditions in icy satellite lithospheres. Cylindrical ice samples with a diameter $D = 25.4$ mm and a grain size $d = 0.3 - 0.5$ mm were formed through the standard ice technique[18]. Samples were then cut into $b = 10$ mm thick pucks and loaded along their diameter. This loading configuration, referred to as a Brazilian fracture test, generates tensile stresses in the center of the sample and vertical fractures that propagate through the sample[19,20].

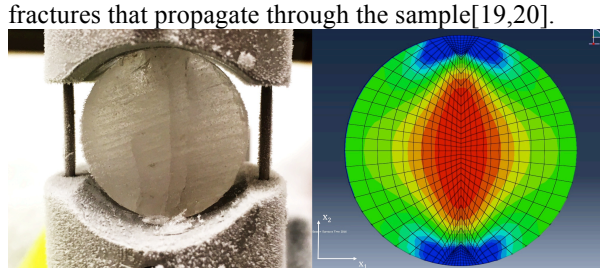

Figure 1: *(Left): OUR ice sample after cyclic Brazilian fracture tests. Curved steel platens reduce stresses at contact points. (Right): Stresses calculated with FEM Abaqus (red=tensile, blue=compressive).*

Tests were preformed in load control with an Instron model 1341, which uses an electric screw driven actuator that is accurate in displacement to the submicron scale. T was controlled by a cryochamber insulated by an ethanol bath cooled by liquid nitrogen.

Two types of fatigue tests were performed. The first test used a constant amplitude sinusoidal load, which was applied until brittle failure occurred or until more than 10^4 cycles were achieved without failure. Unfailed samples were either removed for microstructural analysis or a linear load ramp was applied to measure the monotonic failure load and determine if the previous loading cycles affected the failure stress.

In the second type of test, a cyclic load was applied for N cycles. If failure did not occur the load was continuously increased after an additional N cycles until failure was reached. Failure was detected through sudden load drop and acoustic emissions recorded at 10kHz. The failure load was recorded and converted to stress with the analytical relation [20], $\sigma_f = \frac{2L}{\pi D b}$, which we verified with our numerical model (Figure 1).

Results: We measured a static failure stress of σ_f =1.3 – 1.7 MPa, consistent with previous measurements of ice with a grain size of 0.5 mm[21]. Fracture events were readily detectable in the mechanical and acoustic emission data. Acoustic events were detected during and prior to failure suggestive of microcrack activity. However, in tests with a constant load amplitude of 1.1 MPa, samples did not fail even after experiencing up to 80,000 cycles. The monotonic failure stress of these cyclically loaded samples was similar to the static failure stress. Test with a gradually increasing cyclic amplitude showed a similar result, with failure stress being relatively constant if not increasing with number of load cycles experienced. Microstructural analysis of deformed samples did not show evidence of fatigue crack growth on samples that did not fail. Tests conducted at 198 K and 233 K show consistent results, however tests conducted at 233 K fail at slightly higher stresses, suggesting plastic deformation might have increased the fracture toughness of the ice.

Discussion: Our results suggest fatigue crack growth did not occur during our tests. The lack of weakening behavior we observe is consistent with previous studies that found that cyclic loading may actually increase the brittle yield stress of water ice[16,17].

Its possible that mechanisms other than fatigue may be needed to explain the apparent weak behavior of icy satellite lithospheres. Such mechanisms include the superposition of tidal stresses with stresses from non-synchronous rotation[22] or ice shell thickening. High porosity near the surface due to damage from impact cratering or the presence of brine pockets, could also reduce the brittle yield stress[23].

However, fatigue crack growth may still occur on icy satellites. Lower temperatures may reduce plastic deformation and prevent crack healing and blunting. Additionally impurities such as sulfuric acid may enable stress corrosion and increase fatigue crack growth rates. More experiments are required at even lower temperatures, over longer time periods and under different chemical environments to understand the role of fatigue on icy satellites. Since fatigue crack growth can so strongly influence the strength of the lithosphere, it is crucial to perform these experiments if we want to understand tectonic deformation on active icy worlds such as Europa and Enceladus.

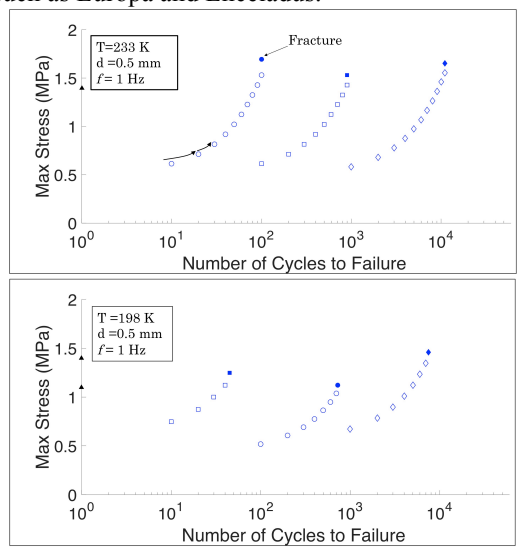

***Figure 2**: Ice fatigue tests with a gradually increasing cyclic load (x-axis=number of cycles, y-axis=load amplitude). Open circles represent samples loaded that did not fracture and were then loaded at higher amplitudes for additional cycles. Solid circles represent failed samples.*

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