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A Fracture Study of Ice Under High Strain Rate Loading

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ABSTRACT

High strain rate compression tests were conducted with columnar ice grown in the laboratory. In addition to measuring stress and strain to failure at 2 strain rates, we examined the effects of end conditions on the failure process. Experiments were performed in a split Hopkinson pressure bar at 2 temperatures, −10°C and −40°C, and a strain rate in the range of 10 to 15 s^{-1}. Additional experiments were performed on similarly grown ice at a lower strain rate of 3×10^{-4} s^{-1} for comparison. In the high strain rate tests, the general observation is that most failures occurred by splitting, and the final failure by collapse of the columns, which become unstable under the sustained load during the passage of the stress wave. Most failures occurred around a value of 1000 microstrain. After crack initiation, failure is progressive, with multiple peaks in the stress–time history, and it takes a finite time for ejection of fragments before the final collapse. Reduction of temperature increases the peak stress values. We also note that although the initial fracture is brittle in nature, the final failure, or collapse, because of time for the fragment ejection, gives the appearance of viscoelastic failure.

INTRODUCTION

Many applications of ice engineering and deicing processes are based on the understanding of the fracture behavior of ice as a material. Other than chemical melting, fracturing of ice either by impact (including blasting) or by deformation of the substrate is the most common practical means to deal with it. Fundamentally, forces need to be applied to overcome the cohesiveness of ice, either by compression, shear or tension, or in their combination, so that the ice is fractured. However, the study of ice fracture is complicated by the fact that ice properties are rate-sensitive, e.g., stress–strain relationships are a strong function of the rate of deformation. As a consequence, it has been difficult to separate rate-dependent effects from pure elastic behavior, and the ice literature is replete with conflicting data about the energy of fracture, which is a critical quantity in any fracture-based analysis. It is well known that in ice both viscoelastic as well as brittle failure processes can occur, depending on the time, temperature and amount of load applied. Schulson (2001) showed it to be a dual process, a competition between crack-tip creep and crack propagation, which controls the ductile-to-brittle transition. The objective of the current research is to identify the limits of both the viscoelastic creep and brittle fracture processes of ice. To do so, we initiated experiments on the fracture processes from high-temperature, slow-rate loading (viscoelastic regime) to low-temperature, high-rate loading (brittle failure regime). This paper gives the results of these initial tests.

To date we have conducted a number of high strain rate compression tests with columnar ice grown in the laboratory. We measured the stress and strain to failure, and examined the size, shape and nature of the fragments, fracture patterns and the effects of end conditions on the failure process. The tests were performed in a split Hopkinson pressure bar at 2 temperatures, −10°C and −40°C, and a strain rate in the range of 10 to 15 strains/s^{-1}. Additional tests were performed on the similarly grown ice at a low rate of 3×10^{-4} s^{-1} for comparison. In the high strain-rate Hopkinson Bar tests, as well as in the low strain-rate, MTS servohydraulic displacement controlled tests, most failures occurred by splitting, and the final failure by the collapse of the columns. The evidence of progressive failure was clear from the multiple peaks of the stress–strain curve in the loading phase. In the high strain rate tests the collapses were not instantaneous, but took a finite time of 100 to 120 microseconds, possibly indicating the time required to eject the fragments. The temperature effect was evident in the small increase of peak stress when the test temperature was lowered from −10°C to −40°C.

BACKGROUND

Depending on strain rate (or rate of loading), ice undergoes either ductile deformation or brittle failure caused by fracturing. With increasing strain rate, the ductile-to-brittle transition depends on the temperature and microstructure of the ice as well as the state of stress. For uniaxial and multiaxial loading of ice, Schulson (2001) and Gratz and Schulson (1997) have presented a theoretical model for the ductile-to-brittle transition strain rate, and the trends

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KEY WORDS: High strain rate, ice compressive strength, ice dynamic response, ice force, ice impact, ice strength, ice temperature effects.