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Dynamic compressive behavior of ice at cryogenic temperatures

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ABSTRACT

In the present study dynamic behavior of distilled water ice (polycrystalline ice Ih) is investigated under uniaxial compression at strain rates in the range of 100 s^{-1} to 1350 s^{-1} and at temperatures in the range of −15 °C to −173 °C using a modified split Hopkinson pressure bar (SHPB). The peak compressive strength is found to increase from 32 MPa to 112 MPa as the test temperatures are decreased from −15 °C to −125 °C. With a further decrease in test temperature from −125 °C to −173 °C the peak strength is observed to remain nearly constant and lie in the range of 110–120 MPa. In addition, the ice samples show positive strain rate sensitivity over the range of strain rates employed in the present tests at test temperatures in the range of −15 °C to −125 °C. However, the sensitivity of the logarithmic of peak stress (strength) to logarithmic of strain rate decreases with decreasing test temperatures, and the ice samples are observed to be nearly insensitive to strain rate at test temperatures lower than −125 °C. An interesting feature of the dynamic compressive behavior of ice is the presence of a shoulder/double-peak in the dynamic stress versus strain curves at test temperatures in the range of −50 °C to −150 °C. Another feature of the post-peak stress regime of distilled water ice is the presence of a long tail in the dynamic stress versus strain curves at a test temperature of −15 °C. At lower test temperatures (from −150 °C to −173 °C) the residual strength of ice is observed to become negligible. These artifacts in the dynamic behavior of ice can be attributed to details associated with dynamic failure of the ice samples and geometric effects emanating from the finite size of the samples and the diameter of the loading bars. The residual dynamic strength of ice can be best understood by considering the damaged/fragmented ice as an assemblage of wet highly-fragmented granular material created by adiabatic heating during grain-to-grain frictional sliding and held together by ice melt and/or recrystallization in the post peak-stress regime.

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1. Introduction

Many fundamental questions regarding preservation of Europa's evolutionary history and possibility of finding life can be best examined by performing in-situ analysis of its ice and oceans (Carr et al., 1998). In this context, a mission to the Jupiter's moon Europa to search for life in its ice-covered oceans promises to provide a unique opportunity to place scientific instruments onto the surface of Europa. Compared with conventional soft-landers that have previously been used in Lunar and Mars explorations, high-velocity kinetic penetrators provide the benefit to access the sub-surface of Europa for onsite sampling and analysis without the need for additional drilling or digging. Moreover, kinetic energy penetrators have the advantage of simplicity and require no sophisticated landing programs for the airless environment on Europa. One of the key challenges faced in the mission is to enable deep penetration of the cryogenic ice crust of Europa to deliver the required scientific instruments for in-situ analysis of the subsurface layers which necessitates a better understanding of the basic impact physics into cryogenic ice. For example, the fundamental thermo-mechanical properties of hard cryogenic ice determine the boundary conditions acting on the projectile, and significantly affect the stress state, peak loads, accelerations, and penetration depth of the penetrator.

There is a considerable body of literature that addresses the dynamic compressive behavior of ice at strain rates in the range from 10^{-2} s^{-1} to 2600 s^{-1} and at temperatures in the range from 0 °C to −30 °C. However, there is little data on the dynamic behavior of ice at cryogenic temperatures in the range from sub-zero to −170 °C. In view of this, an experimental investigation was undertaken at Case Western Reserve University to obtain the dynamic uniaxial compressive strength and failure of ice as a function of loading rate (up to 1500 s^{-1}) and test temperatures down to −173 °C. The data obtained from the present study can be used to validate and/or develop new material models for dynamic behavior of ice at high strain rates and cryogenic temperatures for various planetary and/or engineering applications.

The mechanical behavior of ice is complex. Ice, that can be regarded as a class of materials rather than a single specific material with well-

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defined properties, has thirteen different crystal structures and two amorphous states depending upon its growth temperature and pressure conditions (Klug, 2002; Petrenko and Whitworth, 1999). A relatively large body of literature exists on the compressive and tensile behavior (Currier and Schulson, 1982; Dempsey et al., 1999a; Dempsey et al., 1999b; Haynes, 1978; Jones and Glen, 1969; Petrenko and Whitworth, 1999; Schulson, 2001; Schulson and Duval, 2009; Schulson and Gratz, 1999; Schulson et al., 2005), and fracture properties (Dempsey, 1991; Nixon and Schulson, 1987; Parameswaran and Jones, 1975; Schulson, 1990; Schulson and Duval, 2009; Uchida and Kusumoto, 1999; Weber and Nixon, 1996) of ice. Most of these studies focus on the creep and quasi-static deformation behavior of distilled water ice. Like many brittle materials, ice is stronger in compression than in tension. However, unlike most brittle materials, ice exhibits brittle behavior up to its melting point even at relatively low strain rates (Schulson, 2001).

The compressive strength of ice is sensitive to strain rate and ice exhibits behavior ranging from ductile to brittle under various loading rates. The ductile to brittle transition is understood to occur at a strain rate of 10^{-3} s^{-1} at a test temperature of −10 °C. At higher strain rates, there are relatively few studies on the compressive behavior of ice. The studies by Dutta (1993) and Dutta et al. (2004) suggest that the compressive strength of ice at high strain rates is lower than that obtained under quasi-static deformation conditions. Kim and Keune (2007), using the split Hopkinson pressure bar (SHPB) (Hopkinson, 1914; Kolsky, 1949), reported that the compressive strength of ice is essentially constant at a level of 19.7 MPa in the strain rate range of 400 to 2600 s^{-1}. Other studies on ice at high strain rates indicate that its compressive strength shows positive strain rate sensitivity. For example, study by Jones (1997) show that the compressive strength of ice increases with increasing loading rates over the strain rate range 10^{-1} to 10 s^{-1}, although the data shows considerable scatter. The study by Schulson et al. (2005) shows similar behavior in the strain rate range from 10^{-2} to 1.6 s^{-1}. In a more recent study, Shazly et al. (2006b, 2009) investigated the dynamic behavior of single crystal and polycrystalline ice using SHPB at a range of strain rates from 60 to 1400 s^{-1}. The compressive strengths of both single and polycrystalline ice samples were reported to increase with increasing strain rates. The compressive strength of ice have also been reported to be sensitive to temperature. Studies by Carter et al. (1971) and Schulson et al. (2005) show that the compressive strength of ice increases linearly with decreasing temperatures by approximately 0.3 MPa/K over the temperature range from 0 °C to −50 °C under quasi-static deformation conditions. In addition, Arakawa and Maeno (1997) have shown that under quasi-static uniaxial compression the sensitivity of compressive strength of ice to test temperature is positive in the temperature range from 0 °C to −100 °C, and then the compressive strength becomes nearly constant in the temperature range from −100 °C to −175 °C.

In view of the aforementioned studies the compressive behavior of ice can be summarized as follows. Under quasi-static uniaxial compression the strength of ice increases from 3 MPa to 65 MPa with a decrease in test temperature from 0 °C to −100 °C and then increases rather slowly from 65 MPa to 75 MPa from −100 °C to −175 °C. On the other hand, under high loading rates the uniaxial compressive strength of ice is observed to increase with increasing strain rates in the range 60 to 2000 s^{-1} and at test temperatures in the range −10 °C to −30 °C. Arakawa and Maeno (1997) have attributed the insensitivity of quasi-static compressive strength of ice at test temperatures lower than −50 °C to possible confinement of specimen end faces due to adhesion/freezing of the ice samples to the loading platens. At higher loading rates, however, the end face confinement is negligibly small as per analysis provided by Shazly et al. (2006b, 2009). Therefore, one of the key motivations of the present study is to better understand whether this observed insensitivity of compressive strength with a decrease in test temperature at quasi-static loading rates is carried over to the higher loading rate condition.

In this regards, in the present study, the conventional split Hopkinson pressure bar is modified to accommodate experimentation on ice at cryogenic test temperatures and high strain rates. The paper is organized as follows: in Section 2, the experimental procedure used for the growth of the ice samples and the extension of the split Hopkinson pressure bar for cryogenic temperature testing are described. Section 3 provides details of the experimental results on ice at various strain rates and test temperatures. In Section 4, the experimental results on ice obtained at various strain rates and cryogenic temperatures are compared and a discussion relevant to the experimental results is provided.

2. Experimental methods

2.1. Ice specimens

In the present study, disk shaped ice samples were utilized to conduct the dynamic compression experiments at elevated strain rates and sub-zero temperatures down to −175 °C. Two different ice samples were utilized in the present study. At test temperatures up to −50 °C ice specimens of 19.05 mm diameter and 3 mm thickness were utilized while at temperatures lower than −50 °C ice samples of 11.23 mm in diameter and ~3 mm in thickness were employed to accommodate the increase in ice compressive strength with decrease in test temperatures. Although the ice samples were thin when compared to their diameter, which could constrain radial displacements in the sample during loading and lead to concerns regarding frictional effects, previous study by Shazly et al. (2006b, 2009) have shown that the frictional/adhesion effects at the ice sample/bar ends are expected to be negligible (please refer to Appendix A) since dynamic frictional resistance between ice and aluminum inserts is relatively low at high sliding rates (Irfan and Prakash, 1994; Okada et al., 2001; Prakash and Yuan, 2004; Yuan and Prakash, 2008a; Yuan and Prakash, 2008b).

Besides frictional effects, the stress wave loading used in split Hopkinson pressure bar experiments can cause inertia to have an influence on the measured sample properties, particularly at high strain rates (Graham, 1989). For a sample with diameter d, and an initial length to diameter ratio l_o/d_o, the stresses measured by the output bar, $\sigma_{measured}$, can be expressed as

$$\sigma_{measured}-\sigma_y=\rho d^2\dot{\varepsilon}^2\left[\frac{1}{64}+\frac{1}{6}\left(\frac{l_o}{d_o}\right)^2\right]-\rho d^2\ddot{\varepsilon}\left[\frac{1}{32}-\frac{1}{6}\left(\frac{l_o}{d_o}\right)^2\right]-\frac{\rho l\,\dot{v}}{2} \quad (1)$$

where, σ_y is the actual yield stress of the material, ρ is the density of the material, ad v is the velocity of the interface between the specimen and

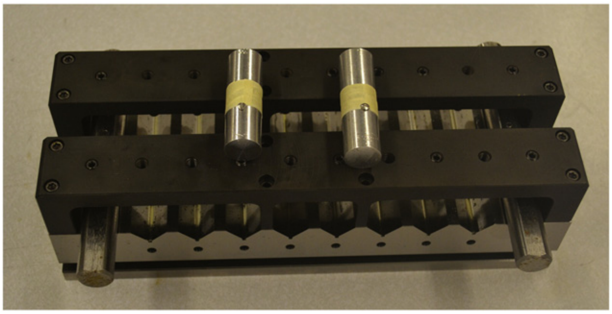

Fig. 1. Method for growing ice samples of 19.05 mm and 11.23 mm in diameter employed in the modified low temperature SHPB designed for conducting uniaxial compression experiments. Two precision matched Vee blocks are used to ensure perfect alignment (parallelism) between the two inserts.

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