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Hydrodynamic modeling of impact craters in ice

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A R T I C L E I N F O

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A B S T R A C T

In this study, impact craters in water ice are modeled using the hydrodynamic code CTH. In order to capture impact cratering in ice, an equation of state and a material model were created and validated. Cratering simulation results correlated well with known experimental results found in the literature with some minor differences that are discussed. An important result from this study was that the simulations showed a proportional correlation between the damaged volume of the ice crater produced by an aluminum projectile and the projectile's momentum. Also, the identification of four distinct stages in the crater development of ice (contact and compression, initial damage progression, crater shaping, and ejected damaged material) is introduced and described.

1. Introduction

Ice is an abundant material found on Earth and on the icy satellites of Jupiter and Saturn [1]. Since Johannes Kepler in 1611 first deduced the hexagonal close packed arrangement of ice in his book [2], ice has been intrigue of many researchers. Understanding ice's dynamic response is necessary to fully characterize the material behavior and studies have been lacking [3–5].

Impact cratering, whether from a modeling or experimental perspective, can provide understanding of the high rate multi-axial behavior of ice. Although laboratory cratering experiments have the advantage of examining the real material as opposed to the simulations, limitations exist such as the size scale related to the experiments and the inability to directly view internal material states while the cratering test is in progress. By modeling and simulation, the evolution of the cratering process and the associated stresses, strains, pressures, and temperatures can be realized. However, an accurate material model especially related to the strength and an accurate equation of state has been lacking for ice. In this paper we present a methodology for high strain rate analysis of ice that employs an internal state variable inelasticity model that is calibrated to experimental high rate uniaxial data, that introduces a new Mie-Grüniesen equation of state for ice, and that uses these models to perform computer simulations using the hydrodynamic code CTH to compare with known cratering experiments.

Various studies have documented different aspects of the high rate ice behavior that are related to the constitutive behavior. Lange and Ahrens [6] studied the dynamic tensile strength (17 MPa) of ice at a strain rate of $2 \times 10^4\ s^{-1}$. Perhaps the most relevant studies pertaining to the strength of ice was conducted by Jones [7] and Shazly et al. [8]. Jones [7] showed in uniaxial compression tests on columnar-grained ice at 262 K for strain rates between $0.1\ s^{-1}$ and $10\ s^{-1}$ the compressive strength of ice increased from approximately 6.3 MPa to 12.6 MPa. Using a Split Pressure Hopkinson Bar (SPHB), Shazly et al. [8] found the increase of compressive strength from 11.7 MPa to 58.4 MPa for higher strain rates (90–1400 s^{-1}). The ice used in Shazly et al. [8] and considered in this study was polycrystalline ice at 263 K, which had a grain size between 1 and 3 mm. The SPHB apparatus is a high strain rate uniaxial compression test. To date, Shazly et al. [8] showed the highest strain rate stress–strain responses in the literature, which were used to develop the material model in this study. Fig. 1 displays the experimental data correlations for Jones [7] and Shazly et al. [8].

In addition to a constitutive model, the crater ice simulations require an Equation of State (EOS) to define the relationship between pressure and material density. For this study, a new Mie-Grüniesen EOS was developed and correlated to the experimental shock wave data for polycrystalline ice garnered by Stewart and Ahrens [9–11].

For fracture of ice, Petrenko and Whitworth [12] provide the most thorough review. At low strain rates $10^{-7}\ s^{-1}$ to $10^{-3}\ s^{-1}$, ice is ductile and deforms plastically by glide and climb from dislocations moving in essentially an HCP crystal. Ice also statically (increased

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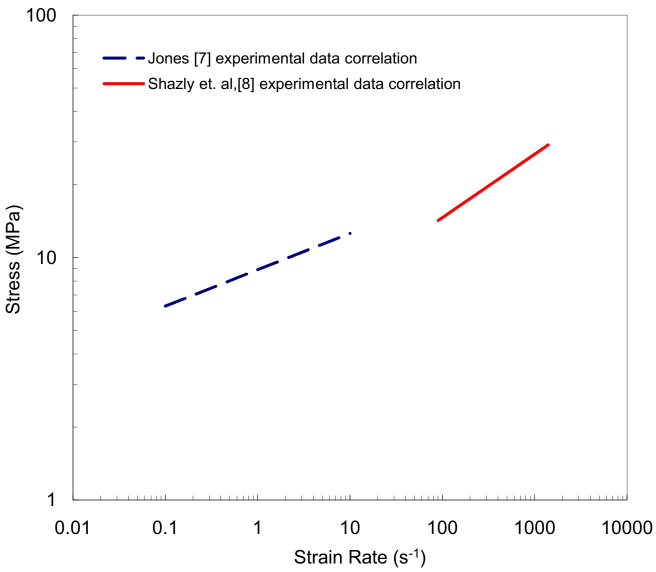

Fig. 1. Stress versus strain rate experimental data correlations for Jones [7] and Shazly et al. [8].

temperature) and dynamically (increased strain rates) recrystallizes. Lower applied strain rates are not relevant to cratering in ice but are important in glacier mechanics. If the strain rate is greater than 10^{-3} s^{-1} and is not confined by a high hydrostatic pressure, ice fails by brittle fracture. When ice is uniaxially compressed at higher strain rates, the material develops wing cracks parallel to the direction of loading [12]. The specimen can fail by splitting, if the wing cracks propagate through the specimen. If the wing cracks interact with each other, the specimen can fail by spalling or crushing. Ice failure by spallation or crush is most relevant to the hypervelocity impacts in this cratering study.

The process of impact cratering has three basic stages as explained by Melosh [13]. The first stage is the contact and compression stage, which is similar in both ductile and brittle material. This stage is where the initial impact shock and compression of the target and projectile is dominant. The next stage, excavation, is where the critical difference between brittle and ductile behavior occurs. For a brittle material in this stage, the shocked material moves at a subsonic rate, and the crater opens by fracturing. The fracturing path determines the final crater shape in a brittle material. The last stage is called modification, where the sides of the crater slump downward by gravity after the shock wave has long passed through the material. The modification stage also includes the erosion that occurs over time after the impact. In this study we are only concerned with the final crater shape resulting from the first two stages.

In order to compare crater simulations to experiments, various velocity ranges have been explored. Kawakami et al. [14], Lange and Ahrens [15], Arakawa et al. [16], and Kato et al. [17] all performed cratering experiments somewhere between the velocity range of 35 m/s and 800 m/s. The research group at the University of Kent at Canterbury in the UK [18–22] extended the velocity range from 1.0 km/s to 7.3 km/s, which provided the experimental results used for the hydrodynamic simulations performed in this study. More precisely, the impact crater experiments conducted by Shrine et al. [20] will be modeled. The impact crater experiments consisted of an aluminum 2017 alloy sphere projectile with a diameter of 1.0 mm and density of 2790 kg m^{-3} colliding with an ice cylinder having a height of 10 cm and diameter of 18 cm. The ice used in the impact crater study was homogenous polycrystalline ice produced at the University of Kent. The temperature of the ice sample just before impact was 259 ± 3K. The velocity of the projectile was varied from 1.0 km/s to 7.3 km/s using a light two-stage horizontal light-gas gun. CTH [23], a Eulerian based hydrodynamic code developed at Sandia National Laboratories, was used to analyze the large pressure waves and large deformations arising in this study.

To the author's knowledge only five papers were found that included the modeling ice at high velocity impacts. Kim and Kedward [24] and Kim et al. [25] both modeled hail impacts on composites using a simple material model in the Lagrangian based finite element code DYNA3D. More recently Carney et al. [5] used a more sophisticated model of single crystal ice for ballistic simulations using LS-DYNA [26]. Also, these authors concentrated on ice as a projectile and not as the target.

Only two of the five ice modeling studies included the cratering process in ice. Tedeschi et al. [27] performed cratering experiments on confined ice targets and then using CTH, simulated a confined and unconfined ice target to compare the hydrodynamic differences. The simulation was designed to analyze the boundary effects on the ice target and was not meant to show the complete crater formation. Another study by Turtle and Pierazzo [28] used CSQ large scale numerical simulations to deduce a lower limit on Europa's ice shell thickness. This simulation was designed to analyze the vapor and melt production of large impacts but not the crater dynamics in the ice shell. Both of these studies did not use a material model in their simulations. At the present no simulations have been completed for the purpose of understanding the cratering dynamics of ice. As such, this paper's contribution is to provide some understanding the cratering process in ice.

2. Method

CTH requires an EOS in order to solve the relationship between pressure and density of the material. In CTH, the only available EOS for ice is the Analytical Equation Of State (ANEOS) model. The ANEOS model in CTH for ice contains the ability to capture the different phase changes in ice, but recent shock wave experiments by Stewart et al. [9] show that this ANEOS correlation does not capture the accurate pressure–density relationship. Fig. 2 illustrates

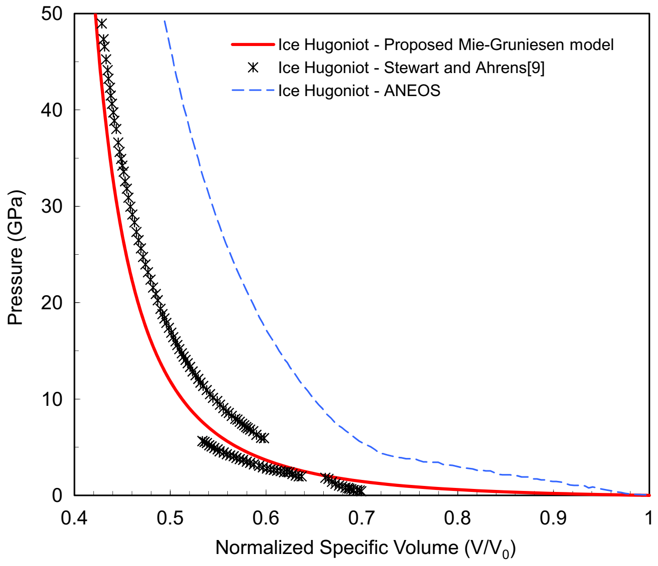

Fig. 2. Proposed Mie-Grüniesen Hugoniot compared to the Stewart and Ahrens [9] data and ANEOS Hugoniots.