INVESTIGATION OF MECHANICAL PROPERTIES OF THE VIÑALES (L6) ORDINARY CHONDRITE.
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Introduction: Most meteorites, which originate from asteroids and comets that survived the passage through the Earth's atmosphere [1], contain useful information for estimating the physical and mechanical properties of asteroids [1,2]. The information is critical for developing hazard mitigation strategies in planetary defense [3]. Due to their highly heterogeneous nature, meteorite properties are influenced by the characteristics of the constituents, their distributions and volume fractions, and preexisting flaws [4,5].

Ordinary chondrite meteorites typically exhibit brittle response under uniaxial compressive load and their fracture mechanisms involve nucleation of tensile microcracks from preexisting flaws. The relative frictional sliding of the flaw generates tension microcracks that deviate at sharp angles from the sliding plane [6]. The micro-cracks eventually coalesce, resulting in axial splitting. Hence, controlled laboratory testing of meteorites are necessary to evaluate the mechanical properties and detailed physical responses.

In this work, the constituents of the Viñales meteorite have been studied using electron probe microanalysis (EMPA) and x-ray micro-computed tomography (XCT). EMPA analysis was used to detect Fe, Ni, and other major elements from Backscattered Electron (BSE) images and correlated with the CT scan images obtained from the XCT. The structural distribution of high-density phases was estimated from the XCT scans, and mechanical properties of the Viñales meteorite were obtained by conducting quasi-static compression tests. Since the limited availability of rare meteorites prohibits conducting a large number of tests that are necessary to fully characterize their mechanical behavior, the knowledge gained from this study could be used to develop physics-based predictive models which can help reduce the number of expensive tests.

Testing and Characterization: Viñales is classified as an L6 ordinary chondrite that fell across the province of Pinar Del Rio, Cuba [9]. Seven 10-mm sized cubes of Viñales were prepared for the laboratory testing to characterize their physical and mechanical properties. One of the samples was used for chemical analysis to identify major and minor elements using electron probe microanalysis with an accelerating voltage of 20 kV and beam current of 58.9 nA. X-ray CT scan was performed on two selected samples using Bruker Skyscan 1272 with x-ray parameters of 100 kV and 100 μA.

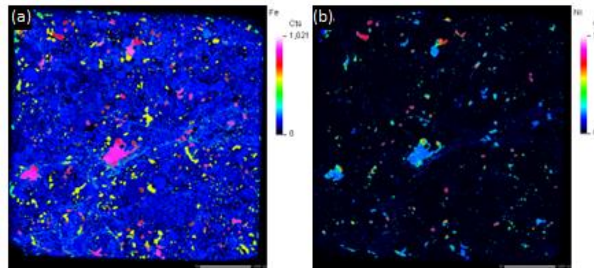

Figure 1. X-ray intensity maps of (a) Fe and (b) Ni from the EPMA showing distribution of different phases such as Fe-Ni metals in red and pink, troilite in yellow, and silicates are in dark blue to black.

A 3.5 μm resolution 3D volumetric density map was generated from the full-volume CT scan to characterize the structure, texture, and grain boundary information of the mineral phases. Quasi-static compression tests were conducted on seven samples with a displacement rate of 0.25 mm/min at room temperature to measure the mechanical properties. The possible impact of the different minerals, such as Fe-Ni metal on the strength of the Viñales meteorite samples, is discussed.

Results: A random distribution of sporadic-shaped bright-colored Fe-Ni metal is identified in a dark-colored irregularly fractured silicate matrix (Fig 1). X-ray intensity maps of Fe and Ni show the areal distribution of kamacite and taenite. The Viñales samples are moderately shocked, belonging to shock stage 4 [9,10]. Multiple randomly oriented shock veins of size <1 mm, two large shock veins of size >3 mm, and an unrecognized chondrule boundary are identified from the CT scan samples.

Further, a non-destructive structural analysis of high-density phases such as Fe-Ni metal was performed by generating a 3D volumetric density map using the x-ray CT scan (Fig 2). Different features such as volume fraction and structural characteristics of Fe-Ni were extracted by thresholding a series of gray images. The results of two CT samples T1 and T2 are presented. Quantitative analysis shows sample T1 has 1.6% metal volume fraction. This analysis reveals a bimodal distribution of Fe-Ni structure with structural thickness ranging from 0.02 mm to 0.7 mm (Fig 2b). In contrast, volume fraction estimated from the XCT analysis of sample T2 show 2.2% of metal.

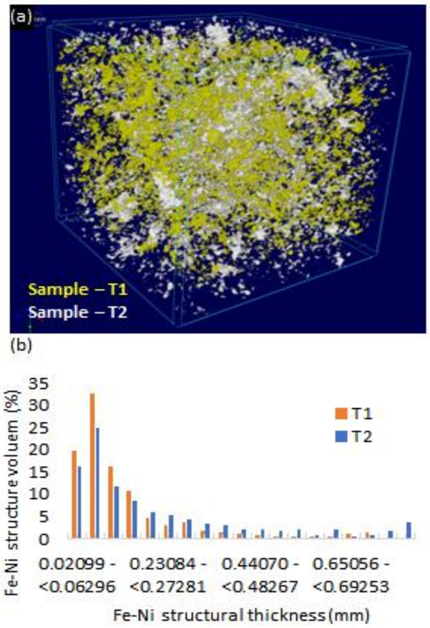

Figure 2. A comparison of (a) 3D density volume (colored as yellow and white), (b) structural distribution of Fe-Ni in two samples (T1 and T2) obtained by XCT scan.

Quasi-static compression tests were conducted to investigate the strength, stiffness, toughness, and strain-to-failure data of the meteoritic samples (Fig 3). All seven samples show brittle behavior in their stress-strain response and exhibit similar failure mode under compressive load. However, the results show variability in the strength data. For example, the ultimate compressive strength ranges from 110.52 MPa to 187. 76 MPa. The variability is likely a measure of the complex mineralogy, heterogeneous microstructure, and variability in element volume fractions, such as those observed with the Fe-Ni phase in the samples (Fig. 2).

It is important to note that silicate phases constitute more than 80% of the volume fraction of the material, are the primary load-bearing elements and contribute to the brittle failure mechanism. The Fe-Ni metals, which are associated with complex dislocation core and slip systems, are responsible for the plastic deformations. Comparing the XCT results of Fe-Ni of CT samples T1 and T2 (Fig 3), the sample with the higher volume fraction of Fe-Ni exhibits slight increase in compressive strength and toughness while sacrificing stiffness. Both samples show a change in the elastic region before final failure indicating crack initiation and propagation as evident from the stress-strain curve.

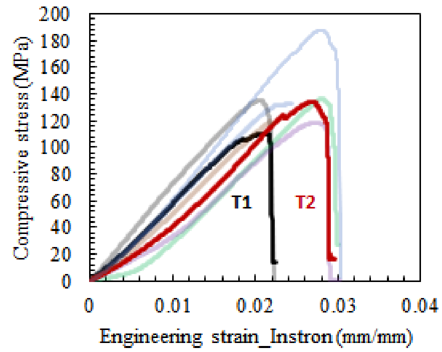

Figure 3. Stress-strain response of the seven Viñales cubes. CT scan samples are T1 and T2 in black and red color. Note, strain results derived from the Instron showed one order of magnitude machine error compared to digital image correlation due to machine compliance and sample settling in the platen.

Concluding Remarks: Preliminary studies have been conducted on the mechanical properties of Viñales meteorites. The ultimate goal of this research is to predict the mechanical properties of pre-impact asteroid, how likely they fragment during the impact events, and their ability to survive passage through Earth's atmosphere [11]. The results from two non-destructive analyses using XCT show a possible correlation between the structural characteristic of Fe-Ni metals and corresponding mechanical properties of the Viñales meteorite, that requires more detailed study. Further investigations are necessary to establish a statistically reliable dataset to obtain a deeper understanding of the possible influence of the distribution of element constituents such as Fe-Ni on the mechanical properties. The knowledge gained will be used to formulate a fracture mechanics based rheological model in a future work.

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