ON THE ROLE OF DEFECTS IN THE DYNAMIC FAILURE OF AN ORDINARY CHONDRITE

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Introduction: An improved understanding of the relationships between the microstructure and the mechanisms that are activated during failure of planetary materials will provide insight into, for example, the processes that govern regolith formation on the Moon [1] and airless bodies [2]. This study is a part of a broader investigation into the competition between impact-driven fragmentation of planetary materials [3] and thermal-fatigue-driven fragmentation [4]. In this study we focus on impact-driven fragmentation. Here, we investigate the fragmentation of an ordinate chondrite, GRO 85209, to better understand the role of defects on failure. To accomplish this, high-speed photography is coupled with dynamic compression testing techniques using a Kosky bar. Nano-indentation measurements are performed to probe constituent properties of the microstructure, and optical microscopy is used to identify macro-scale failure mechanisms. We also apply image processing techniques to optical images to determine fragment size and defect spacing. The latter techniques were developed in Hogan et al. [5].

Meteorite Material: The meteorite material is GRO 85209, an L6 ordinary chondrite that was found in the Grosvenor Mountains (GRO), Antarctica [6]. An optical image of the GRO 85209 microstructure is shown in Fig. 1a. GRO 85209 primarily consists of low-Ca pyroxene (matrix material), and iron nickel [6] (both are highlighted in Fig. 1a), with some olivine and chondrules (not seen in Fig. 1a). This meteorite has a density of 2,996 kg/m\textsuperscript{3} and a Young’s modulus 14 GPa. Nano-indentation experiments indicate that the Young’s modulus of the pyroxene is 95±3 GPa, and for the iron-nickel 178±6 GPa.

Results and Discussion: We investigate the dynamic uniaxial compressive failure as shown in Fig. 2. The stress-time history of a Kolsky bar experiment is shown on the left. Eight time-resolved high-speed camera images are shown on the right and the times at which the images were taken are plotted at corresponding values of stress using single black points on the left. The peak stress for this experiment is ~220 MPa. We do not observe any failure features on the imaged surface until image 4, where we use an arrow to highlight a fracture originating from the right edge and propagating down and to the left. Internal fractures are likely initiated and have grown prior to the observation of this surface crack. As a result of fracturing, the stress in the sample collapses. Additional fractures are observed on the surface at times 5 and 7. At much later times, these cracks coalesce to form fragments. These fractures propagate at speeds of 500±90 m/s, and the cracks are near horizontal (along the loading direction). We investigate internal failure features of the fragments in Fig 1b. To obtain this image, fragments were mounted in resin and systematically polished through their cross-sections. In Fig. 1b, iron-nickel grains (white features) are observed to intersect the outer fracture surface. There are also many internal fractures, and these also intersect the iron-nickel grains.

Finally, the cumulative distribution of fragment sizes is plotted in Fig. 3 for a quasi-static (strain rate of 10\textsuperscript{-3} s\textsuperscript{-1}) and dynamic (10\textsuperscript{3} s\textsuperscript{-1}) experiment. There is an inflection point in the size distribution at approximately 120 microns, and this possibly suggests two fragmentation mechanisms. To investigate this further, we also plot the cumulative distribution of iron-nickel defect spacing in Fig. 3. It appears that the inflection in the size distribution approximately correlates with the iron-nickel grain spacings, suggesting that they may be related.

Summary: The effect of microstructure on the compressive failure of an L6 chondrite meteorite has been examined. Iron-nickel phases have been identified as major heterogeneities contributing to fracture and failure. This may be a result of the stiffness mismatch between the iron-nickel and adjacent pyroxene phases. Failure of this material results in two fragmentation mechanisms: (1) a mechanism that creates smaller fragments that is associated with the the activation and coalescence of fractures between adjacent iron-nickel grain, and (2) a mechanism that creates the larger fragments that is associated with the structural failure of the sample (i.e., coalescence of the larger fractures observed at later times in Fig. 2).


Acknowledgements: This work was also supported by the Solar System Exploration Research Virtual Institute (SSERVI) NASA Cooperative Agreement NNA14AB02A.
Fig. 1. Optical microscope image of (a) GRO 85209 microstructure with labeled iron-nickel grains inside a predominantly pyroxene matrix, (b) internal failure features inside a large polyphase fragment with iron-nickel grains appearing to play an important role in fracture.

Fig. 2. Stress-time history of uniaxial compression experiment (left) with time-resolved high-speed camera images of failure on the specimen surface (right). The arrows are used to denote fractures, the specimen is 5.3 mm in length.

Fig. 3. Cumulative distributions of fragment sizes for quasi-static and dynamic experiment. Also plotted is the cumulative distribution of iron-nickel grain spacing. Note that the inflection in the fragment size distribution appears to be related to the iron-nickel grain distributions.