In-situ visualization of dynamic fracture and fragmentation of an L-type ordinary chondrite by combined synchrotron X-ray radiography and microtomography

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Abstract

The relationship between the dynamic mechanical properties of stony meteorites and their microstructures was investigated *in-situ* for an L-type ordinary chondrite using a split-Hopkinson pressure bar apparatus and ultra-high speed phase-contrast X-ray radiography at the European Synchrotron Radiation Facility (ESRF). Synchrotron X-ray microtomography (µCT) was performed both prior to and immediately following dynamic compression to correlate key structural features between the initial microstructure and recovered fragments as well as to identify the leading mechanisms for fracture and fragmentation. Real-time visualization of damage evolution in the specimens revealed the very first cracks to be initiated at the sites of FeNi-metal nodules. These cracks propagated rapidly through the largest group of chondrules (the porphyritic olivine type chondrules) along the loading direction, which led to the formation of column-like fragments. µCT analysis of the collected fragments confirmed the dominant mode of fracture to be transgranular with a clear link between FeNi-metal nod-

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ule statistics and the size distribution of fragments, emphasizing their role in mechanical failure and fragmentation process. The resulting fragmentation was used to validate the predictions of brittle fragmentation models, and found to be in good agreement with the laboratory-scale impacts. In turn, these models can help unravel the consequences of impact-induced fragmentation processes that have helped shape the solar system.

Keywords: Ordinary Chondrite, Synchrotron X-ray Radiography, Dynamic Compression, Fracture, Fragmentation

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1. Introduction

Our solar system is populated by millions of asteroids, comets and other cosmic debris (Cochran et al., 1995; Wiegert and Tremaine, 1999; Tedesco and Desert, 2002; Charnoz and Morbidelli, 2007). These objects can be classified based on their characteristic emission spectra into three main groups: C-type (made of carbon and organic compounds), S-type (made of silicate rocks with small amounts of iron), and M-type (made of metallic and sometimes also non-metallic compounds) (Chapman et al., 1975; Morrison, 1977b,a). Such a wide range of compositions of asteroids is reflected in their diversified physical properties, such as density, solidity, structure or thermal behaviour (e.g. Flynn et al., 2017; Ostrowski and Bryson, 2018). It is thus of utmost importance to understand their microstructures and physical properties to help develop prevention strategies for asteroids which cross Earth's orbit in a similar trajectory or to better understand collisions in the early solar system.

In view of the above, and among all types of asteroids, chondrites are the most primitive objects present in our solar system. They provide a record of early solar system processes that make them attractive as a model material for fundamental research in space and planetary science (e.g. Wasson and Kallemeyn, 1988; Scott and Krot, 2003). Chondrites also represent the largest group of the terrestrial meteorite population (82% of observed falls (Grady, 2000)), and the reason for this is that these meteorites are tough and resistant to breakup during passage through the Earth's atmosphere. Hence, these stony meteorites are very important from the perspective of planetary impact and the damage it can cause. In addition to that, chondrites contain a range of phases and microstructural features incorporated to some degree in other classes of meteorites. Thus, the experimental efforts towards a better understanding of fundamental mechanisms leading to fracture and fragmentation, or providing a link between the microstructure of meteorites and their dynamic failure response are a matter of great importance.

The goal of this study is to probe the dynamic behaviour of stony meteorites and expand our knowledge about the potential mechanisms of energy dissipation involved in post-impact fragmentation of asteroids present in our solar system. Such knowledge can further facilitate the exploration of various scenarios for asteroids as small as a few meters in diameter and involved in dynamic events, such as a collision between two asteroids, an asteroid impact on Earth, or a projectile colliding with an asteroid. Under such events, the asteroid target can release an extremely large amount of energy in a very short time. For example, a collision of two asteroids having few kilometres in diameter (1.1–1.9 millions of asteroids in the Main Asteroid Belt have a diameter larger than 1 km Tedesco and Desert (2002)) at a speed of about 5 km/s (which is the mean collision velocity of two asteroids Bottke et al. (1994)) could result in extremely high pressures (10^{11} Pa), strain rates (10^5 s^{-1}) and temperatures ($>10^3$ K) localised in small domains of the asteroid's bodies (Ramesh et al., 2015). Farther away from the impact domains there is less energy that needs to be dissipated, and the present loading conditions favour fragmentation rather than accretion. Thus, the investigation of post-impact fragmentation requires an experimental approach in which the material can experience pressures up to roughly 1 GPa and undergo deformation at strain rates of 10^2–10^3 /s (impact events in the low-velocity regime, <1 km/s) (Ramesh et al., 2015). Under such conditions, failure of the material can be controlled by complex interactions of cracks, shear bands or formation/collapse of voids, the details of which are obscured to conventional diagnostics.

This study therefore proposes an experimental approach combining a dynamic compression testing apparatus and ultra-high speed phase-contrast X-ray radiography on Beamline ID19 at the European Synchrotron Radiation Facility (ESRF) (Weitkamp et al., 2010). This synchrotron radiation source provides unique opportunities for real-time X-ray imaging of subsurface dynamics in opaque materials, thus allowing for visualisation of subsurface microstructural changes (mechanisms leading to failure) in the specimens undergoing dynamic deformation. It should be noted that this is the first experiment at ESRF–ID19 that covers these loading conditions and the first combined synchrotron X-ray radiography and X-ray microtomography (µCT) experiment on a dynamically-loaded meteorite material studied at the mesoscale with such details. Hence, these experimental efforts can provide a link between the microstructure of ordinary chondrites and the failure mechanisms in the low-velocity impact regime. Also, the results of this study can help to understand the importance of chondrules, and their morphology, structure and composition to the dynamic failure process.

2. Material

2.1. Overview and Preparation

A meteorite called NWA 5477 (Meteoritical Bulletin Database, 2016) has been chosen for this study as a model material system. This L-type ordinary chondrite was discovered in the Sahara Desert in 2008, and classified as an L3.2 chondrite, weakly shocked (shock stage of S2), and with little or no weathering (weathering grade of W1). Figure 1 shows an optical micrograph of a thin section of the sample. This piece is approximately 37 mm × 23 mm (∼830 mm^2), and is irregular in shape with rounded external edges. The overall density of this fragment of meteorite was found to be about 2740 kg/m^3. The sound speed measurements were made through the thickness of the sample and found to be

5685±100 m/s and 3684±30 m/s for the longitudinal and shear waves, respectively. The texture and composition of this ordinary chondrite is believed to be relatively unaltered by the heat generated during atmospheric passage, and so its properties are very much akin to that of the parent body. Further information can be found in the Meteoritical Bulletin Database of the Meteoritical Society (Meteoritical Bulletin Database, 2016).

The chondrite has been sectioned with a water-cooled diamond saw such that six test specimens with a cross-section of 3.1 mm × 2.8 mm (width× height) and length of 4.9 mm (tolerance of all dimensions: ±0.05 mm) were obtained. The specimens were then polished using a series of abrasives, finishing with a 4000-grit SiC paper, and examined using an optical microscope. All the specimens were subsequently imaged using synchrotron X-ray µCT (ESRF–ID19) to reveal the 3D morphology of chondrules, mineral fragments and metals in the matrix assemblages.

2.2. Microstructure

The basic mechanism of dynamic fracture in terrestrial rocks and other brittle materials is linked to the initiation, propagation and coalescence of cracks from intrinsic microstructural features (minerals, metals, pores, etc.). Each chondrite found on Earth contains a unique composition of microstructural features, each of which influence, to a greater or lesser degree, the dynamic failure process. It is therefore important to discuss the microstructure of this type of material in more detail.

From Fig. 1, it is observed that this fragment of meteorite contains large and well-defined chondrules of various petrological types in fine-grained matrix assemblages. The chondrules are largely spherical, sub-spherical or ellipsoidal in shape and their mean size was determined to be ∼700 µm (Meteoritical Bulletin Database, 2016). It should be noted that only some of the chondrule textures and mineral agglomerates can be presented here since they are highly diverse in their properties. These are shown in Fig. 2 as the synchrotron X-ray µCT images of non-destructive sections through the reconstructed volume of the test specimens with an isotropic voxel size of 2 µm (more about data acquisition in Section *'Time-resolved Experiments'*).

The largest textural group of chondrules in this material is *porphyritic*. An example of the *porphyritic olivine* (PO) type chondrule is shown in Fig. 2a (the edge of the chondrule is marked by the dashed line). These chondrules are composed of large euhedral olivine crystals immersed in a homogeneous glassy *mesostasis*. Such texture is typical of FeO-rich (Type-II) PO chondrules. Some FeO-poor (Type-I) PO chondrules, which characterise small anhedral olivine crystals, were also observed. In the PO chondrules, it is very common to observe randomly oriented crack patterns in olivine crystals. Also, some chondrules have developed microcracks or micropores. Note two microcracks originating from the matrix assemblages on opposite sides of the chondrule indicated by the arrows in Fig. 2a. These cracks are likely the result of low-velocity impact or residual stresses during the accretion stage of the parent body. In the context of this study, it is worth emphasising that the pores and microcracks play an important role in the failure process of brittle materials subjected to mechanical loads.

Another example of such stress-induced microcracks at the interfaces between agglomerated chondrules is shown in Fig. 2b (indicated by the white arrows). Here, the concentrated stresses were large enough to initiate and propagate cracks in most of the chondrules. However, in certain melt compositions these interfaces could act as a preferred nucleation site for new structures. Note that the 'skeletal' structures, which are present in a central chondrule, likely nucleated at these interfaces (such 'skeletal' structures were previously reported in olivine crystals in Donaldson (Donaldson, 1976)). This might suggest that during the accretion stage of the parent body, the cooling rate was different for each chondrule precursor. The deformed shape of this central chondrule also suggests its higher body temperature than that of the surrounding chondrule precursors. Nonetheless, most olivine crystals maintained silicate heterogeneity and apparent zoning, which is consistent with the L3-type chondrites.

Other energy relaxation mechanisms, such as twinning or cleavage, are often observed in the *porphyritic pyroxene* (PP) type chondrules. An example of such chondrules is shown in Fig. 2c (also, indicated by the black arrow in Fig. 2b). Note that the mechanism of contrast formation in the X-ray phase-contrast µCT imaging technique is related to changes in the complex refractive index of X-rays as they pass through the specimen, and so the twinning planes cannot be distinguished from one another on µCT scans. The presented chondrules form sub-rounded aggregates of grains associated with *pyroxene* and abundant FeNi-metal nodules (indicated by the black arrows). The PP type chondrules, however, are rare and the mixtures of *olivine* and *pyroxene* dominate in the material (Fig. 2d). The interiors of the *porphyritic olivine–pyroxene* (POP) chondrules are generally occupied by *olivine* grains surrounded by either rims of *pyroxene* crystals (indicated by the white arrow in Fig. 2d) or rims of *pyroxene* and FeNi-metal aggregates (indicated by the black arrow in Fig. 2d). Such armored chondrules are very common in low-petrologic type chondrites. As with pores and microcracks, the *pyroxene* crystals and FeNi-metal aggregates might act as stress concentration sites and cause strength degradation, premature failure, and affect the fragmentation process.

Among other chondrule textures reported in the material are *radial pyroxene* chondrules and *barred olivine* chondrules (not shown here). These are the most spherical chondrules likely formed from rapidly quenched liquid spheres. Some evidence for such rapid quenching (or rapid cooling) is shown in Fig. 2e. This figure presents a few PO chondrules (indicated by the black arrows) with small olivine fragments set in a fine-grained matrix assemblages of similar composition. The arrangement and morphology of these 'frozen' chondrules suggest they were likely created by an impact event, which ejected them away as small droplets (similar to the motion of water drops rebounding from a plane water surface upon impact). These droplets consequently quenched rapidly and combined with the dusty precursor material that bound them together.

The observed morphology of chondrules suggests that this chondrite has much in common with volcanic breccias and, as its counterpart, has formed in a dust-rich environment at elevated temperature (<600 °C (Huss et al., 2006)).

The complexity and heterogeneity of various structures formed by chondrule precursors suggest that they must have cooled very quickly so that various chemical reactions inside the chondrules were not completed, and metals and silicates remain separated (Fig. 2a–e). During this forming stage, the chondrule precursors were able to collide in 'pliable' states, undergo deformations and merge together (Fig. 2b and Fig. 2e), progressively forming different forms of dynamic or shock metamorphism. Such examples are the brecciation (Fig. 2a) and veining (see veins of *pyroxene* originating from the PP chondrule indicated by the black arrow in Fig. 2b) preserved in the olivine minerals. Both likely resulted from local impact melting of the rock and injection of this melt into preexisting fractures. Other signs of shock melting in the material are small irregular droplets of metal (see the matrix assemblages in Fig. 2a–e). Finally, the presence of irregular microcracks suggests low-velocity impact or the presence of static stresses during the early stages of chondrite formation (Fig. 2a–b). These aforementioned microstructural features are common amongst the various chondrite groups. As a matter of fact, it is believed that chondrites, which are petrologically, chemically, or isotopically similar result from ejection events that occurred on the same or similar parent bodies Heymann (1967); Crabb and Schultz (1981); Marti and Graf (1992); Keil et al. (1994); Bogard (1995); Gaffey and Gilbert (1998). Therefore, a better understanding of the failure mechanisms in this class of chondrites can help us better understand the properties of other meteorites formed through similar creation processes.

3. Experimental Methods

3.1. Time-resolved Experiments

Dynamic compression experiments were performed at ESRF–ID19 using a split-Hopkinson pressure bar (SHPB) apparatus and synchrotron X-ray radiography. A schematic diagram of the experimental setup is presented in Figure 3. The synchrotron source was about 145 m away from the experimental hutch, while the distance between the specimen and the scintillator ($\sim$8 m) was within the near-field diffraction of 'hard' synchrotron X-rays. The ESRF storage ring was operated in the '16-bunch' filling mode (90 mA maximum stored current) which provided X-ray pulses with a pulse width of $\sim$100 ps (full-width at half-maximum) and the time between electron bunches of about 176 ns (ESRF Accelerator & Source Division, 2019). The main characteristics of Beamline ID19 is a high photon flux density, a high degree of (partial) spatial coherence at the specimen position, a spatial resolution at the micrometer scale and large native beam size. The X-ray beam size was adjusted by a combination of horizontal and vertical slits to be 10 mm × 10 mm, which covered the entire specimen and surrounding region during the whole dynamic compression experiment. The X-ray beam transmitted through the specimen was converted to visible light by a LYSO:Ce single-crystal scintillator (Hilger Crystals, UK) having a diameter of 25 mm and thickness of 220 µm. The light emitted by the scintillator was relayed to two synchronized high-speed cameras by a mirror, diverted by a 50/50 beam splitter, and collected by Nikon AF-S NIKKOR 50 mm f/1.8 lenses attached to the cameras. Each high-speed camera (Shimadzu HPV-X2) recorded 256 radiographs per experiment with an interframe time of 880 ns (equal to approximately five bunch separations) and an exposure time of 200 ns. It should be noted that the scintillator emission decreased to zero between the bunches (decay of a LYSO:Ce scintillator is about 41 ns (Pidol et al., 2004)), thus reducing ghosting artifacts on the captured radiographs to minimal levels (Fig. 3b) (Rutherford et al., 2016; Olbinado et al., 2017). More details of the imaging system can be found in Escauriza *et al.* (Escauriza et al., 2018).

Figure 3 also presents a schematic of the SHPB technique for the dynamic compression experiments. The SHPB bars and projectile were 6 mm in diameter, and made of ultra-high-strength maraging steel (Grade 350). The length of the input and output bars was 1 m, while the projectile was 0.4 m long, corresponding to a pulse length of $\sim$170 µs. The cuboidal specimen was 'sandwiched' between the input and output bars, and the centre of the specimen horizontally aligned with the bars and the X-ray beam axis prior to the test. Lubrication was provided by placing vacuum grease between the specimen ends and bars to reduce the interfacial friction during the test. The specimen domain was enclosed within a thin-wall polycarbonate box to collect the resulting fragments for subsequent X-ray analysis.

A crucial step in the implementation of high strain rate compression experiments at ESRF–ID19 was synchronization of the SHPB system with the synchrotron radiation source. This was achieved using the X-ray bunch clock (radio frequency clock) and the electrical signal from the digital delay generator in the following manner. First, two independent pulse outputs of the delay generator were used to open the fast beamline shutter (allowing the X-ray beam to enter the hutch) for several hundred ms, and fire the SHPB system such that the loading of the specimen occurred in this time window. The projectile was fired against the incident bar at a prespecified velocity ($\sim$8.5 m/s). This impact event generated an elastic compression wave which traveled along the input bar towards the specimen. The signal of this wave was recorded (as a function of amplitude in time) by the strain gauge located in the middle of the incident bar. When the compressive wave front reached this position (which is manifested by a negative change in resistance across the strain gauge circuit), both high-speed cameras were triggered at a specific time delay since the time required for the compressive wave to reach the specimen was known *a priori* to a precision of ±1µs. The cameras were configured to interleave sequential X-ray pulses (Fig. 3b), effectively doubling the overall frame-rate of the dynamic radiography sequence.

3.2. Microtomography

The tomographic data were acquired at the same experimental hutch (ESRF-ID19). The static nature of the scans required a configuration with less photon flux density and reduced energy bandwidth to increase the sensitivity of tomographic optical images. A photon energy of around 35 keV was chosen to ensure a sufficient transmission through the specimen, which was similar to the ultra-high speed imaging configuration. The beamline was operated in white mode to reach sufficient photon flux density while maintaining a homogeneous wave front for phase-contrast imaging. A set of attenuators (5.6 mm Al, 1 mm diam, 0.14 mm Cu) together with a Be exit window (0.5 mm thick) were the only (mandatory) X-ray optical elements in the beam path. The attenuators were used to suppress the fundamental harmonic of the source, which resulted in a broad peak spectrum of around 35 keV. The source was a U17.6 type single-harmonic undulator set at a gap of 13 mm. The detector consisted of a pco.edge camera (PC AG, Germany) with two lenses (Hasselblad lenses facing each other in tandem-like design) coupled to a single-crystal scintillator (Ce-doped Lu3Al5O12) with an effective pixel size of 2.16 µm. A propagation distance of the X-ray beam between the specimen and the detector ($\sim$200 mm) was optimised to yield the best sensitivity of the technique to interfaces between different microstructural features in the specimen. Each tomographic data set resulted in 5000 projections (0.125 s exposure time) recorded over 360° rotation. The images were obtained without the phase retrieval algorithm.

The reconstructed image data was then used to estimate a percentage share of constituent phases and pores in each specimen. This process consisted of the following steps: (i) defining a region of interest (ROI) limited by the specimen's edges; (ii) plotting the histogram of all images; (iii) manually selecting threshold values for each phase by finding the local maxima and minima of histogram; (iv) creating binary images based on the threshold values; (v) calculating the volume fraction of constituent phases as $V_f = (V_p/V_{tot}) * 100\%$, where: V_p is the sum of the pixels in the selection, and V_{tot} is the total number of pixels in the ROI. It should be mentioned here that such approach has some limitations in the assessment of the porosity, as the pore size below the voxel size (2 µm) cannot be resolved. Thus, the porosity levels reported here should be interpreted with caution (Njiekak et al., 2018). The image analysis was performed in the Fiji distribution of the ImageJ software (Schindelin et al., 2012).

The reconstructed image data of the collected fragments of the specimens were analysed in the same image processing software using the 3d object counter function (Bolte and Cordelières, 2006). This method operates on binary images, which were created based on the manually selected threshold value from the cumulative histogram. As a result, the quantitative and morphological characteristics of the fragments, such as the count distribution, the volume distribution, and the side lengths of the smallest bounding box encompassing the fragment were obtained, among others.

4. Dynamic Response

4.1. Dynamic Compression Experiment

Figure 4 presents a schematic diagram of one of six dynamic compression experiments (Fig. 4a) and the results in the form of a stress-time history (Fig. 4b). This particular specimen was chosen because of its heterogeneous microstructure with chondrules of various petrological types, and radiographs with the best contrast. Note the direction of the X-ray beam and the locations of X-ray virtual µCT slices indicated in the schematic, which are shown in Fig. 5c. The stress-time history, on the one hand, highlights the acquisition times of the X-ray images for both high-speed cameras and the time position of radiographs shown in Fig. 5a.

The stress-time curve exhibits three distinct regions. In the first region (Stage I), the stress in the specimen builds up from zero to peak stress in three consecutive steps. Next, a well-defined plateau at the post-peak stage can be observed (Stage II), which is then followed by a stress drop (Stage III). In the initial step of the first stage of loading (stress range from 0 to 220 MPa), the stress increased at an average rate of 50±4 MPa/µs. The rate then decreased to 27±2 MPa/µs for the stress range of 220–300 MPa, and increased again to a level of 70±3 MPa/µs, notably higher than the average stress rate during the first stage of loading. The cause of this difference can be seen by looking at the corresponding time series of radiographs, shown in Fig. 5a.

Note that radiographs 1 and 2 in Fig. 5a, which correspond to near-zero stress and the first stage of loading, show no structural changes in the specimen. However, the first cracks can be observed shortly before and after the second stage of loading, as indicated by the black arrows in radiographs 2–3 in Fig. 5a. The cracks are also shown in detailed views of the specimen, which has been magnified, contrast-enhanced and colour-inverted to aid visibility (i.e., the cracks appear as dark regions). The degree of structural changes visible in the radiographs can also be compared with a synthetic high-resolution transmission image (Image I in Fig. 5c) constructed from an average image of all µCT slices along the X-ray beam direction (as shown in Fig. 4a) and presented in inverted grayscale. It is likely that the nucleation of these very first cracks was responsible for the observed decrease in the stress rate. Interestingly, these cracks developed at or near the interface between dark and bright features. It is worth noting here that minerals with higher atomic number Z (or higher density phases) appear as dark regions on radiographs due to higher attenuation of the incident X-ray beam, which is opposite to µCT slice images (Images II–IV in Fig. 5c) in which these minerals appear hyperdense (bright white). Consequently, a direct comparison of radiographs and microtomographs of the specimen suggests that the cracks developed near the PP chondrules associated with *pyroxene* and FeNi-metal nodules. For example, the crack indicated in radiograph 2 in Fig. 5a likely nucleated at the interface between the FeNi-metal phase and the adhering PO type chondrule, as shown in µCT scan 2 in Fig. 5c (indicated by the black arrow).

At this stage of loading, although microscopic damage has begun to accumulate (but is not discernible given the resolution of the radiographs), the specimen core remains intact. These observations are supported by the data in Fig. 5b, where the waterfall plots of the normalised pixel intensities along the paths indicated in radiograph 1 in Fig. 5a. are traced over the duration of the dynamic compression experiment. Note that the time taken to reach the peak stress of 469 MPa was about 11.6 µs and the amount of pixel intensity variation within this period of time is rather small in each region, and considered to be the noise associated with the image acquisition system. Thus, the continuous and compressive load causes the material to compact and limits the process of opening of microcracks. These provide subtle changes in the density, impedance and geometry of the specimen, which are reflected in higher stress rates. This is because the stress state in the specimen builds up by multiple reflection of stress waves, and the reduction in length of the specimen or its higher density can dramatically affect the mechanical response of the specimen (as in this case).

The following plateau in compressive stress (the second region in the stress-time curve) lasts for approximately 4.1 µs. The number of visible macroscopic cracks is still low at the peak stress level (as shown in radiograph 4 in Fig. 5a) and in the consecutive post-peak stage (radiograph 5 in Fig. 5a). However, there are some visible signs of damage at the upper and lower edge of the specimen (indicated by the arrows), and some in the middle (also captured by the increased pixel intensity in the LP2 plot in Fig. 5b). After the plateau, the stress decays to zero within ∼16.3 µs, and this gives the total time of ∼32 µs for the entire experiment. At this final stage of the test (>20 µs), the stress relaxation is accompanied by extensive cracking and fragmentation, as captured by the increased pixel intensity in all three waterfall plots in Fig. 5b (i.e.: the larger the separation between two fragments of the specimen, the less the attenuation of x-rays by absorption offered by the material of a given thickness). The following radiographs also provide more insight into the process of failure. For example, note the cracks (indicated by the black arrows in radiographs 6 and 7 in Fig. 5a) that developed between two chondrules with dark rims (indicated by the white arrows in these radiographs). Both features were identified as the PP chondrules associated with *pyroxene* and FeNi-metal nodules. These chondrules can be seen in µCT scans 1–2 in Fig. 5c (indicated by the black and white arrows). Thus, the population of the PP chondrules, while small, might be important for understanding the failure mechanisms and fragmentation of this ordinary chondrite for the investigated loading conditions.

To this end, it can be generalised that the specimen failed in a brittle fashion with little plastic deformation, and the failure was mostly controlled by the propagation of transgranular cracks. Nevertheless, the intergranular fracture mode (or combination of crack deviation and arrest) along the PP chondrules was also observed. The average crack tip propagation speed was estimated to be at least 2.4±0.6 km/s. This value was determined based on the average of 26 observations from transgranular cracking in all experiments, and the given spatial and temporal resolution of the imaging system. Due to uniaxial loading conditions, most of the cracks propagated near-parallel to the compression axis, which resulted in the formation of column-like fragments. These column-like fragments were subsequently reduced to smaller fragments due to the buckling and the erosion of ejected fragments.

Each specimen was tested under similar loading conditions (impact velocity of 8.48±0.06 m/s) and, despite differing microstructural characteristics, exhibited similar specimen failure times of 32±2 µs. The average peak stress, stress rate and strain rate were calculated to be 578±90 MPa, 55±9 MPa/µs and 815±127 /s, respectively. Note that the spread in measured strength values is typical of brittle materials, and is due to their intrinsically low toughness and sensitivity to defects and imperfections present in the microstructure. Furthermore, the particular manifestations of these defects (e.g. size, spatial and orientation distributions, etc.) can strongly contribute to the variability in effective strength of the bulk. A more complete picture of how the microstructure might affect the response of the specimen to dynamic loading is obtained by the analysis of µCT data.

4.2. Strength and Microstructure Characteristics

Figure 6 shows the measured peak stress values against the volume fraction of the PP chondrules, FeNi-metal nodules and porosity in the corresponding specimens. Interestingly, the presence of PP chondrules does not substantially affect the mechanical behaviour of the material. On the other hand, the increasing volume of FeNi-metal nodules and microporosity have a noticeable effect in lowering the mechanical properties of this chondrite. The effect of size and spacing of FeNi-metal nodules on the strength of the chondrite is presented in Figure 7. Note that the strength is predominantly controlled by the largest FeNi-metal nodule. The average size of these metallic inclusions (45±1 µm) and the average spacing between them (176±9 µm) are very similar across all the specimens, and their influence on the load carrying capacity of the specimen is not clear. More experiments, together with statistical treatment of data, would be beneficial to confirm these observations. In addition to the above discussion, one should be aware that the variability in dynamic strength measurements of brittle materials is admittedly more complex than this, and involves a competition between the dynamics of crack nucleation from critical defects, crack growth, and the loading rates. However, these are difficult to quantify and expected to be comparable for all experiments due to the same loading conditions.

5. Fragmentation

Following the dynamic tests, several fragmented specimens were characterised using synchrotron X-ray µCT to elucidate the role of chondrules and their morphology in the dynamic failure process. The results from one of these post-experiment scans are presented in Figure 8, in which a schematic illustration of the polypropylene tube containing fragments with superimposed contours of longitudinal and transverse cross-sections of the tube is shown in Figure 8a, and the corresponding µCT images of these cross-sections are shown in Figures 8b–f. Based on the µCT images of collected fragments, it can be seen that the dynamic compression experiment resulted in a relatively wide range of fragment sizes extending from micrometer- to millimeter-sized debris. These observations are in line with a real-time visualization of the failure process, which showed (i) the presence and evolution of randomly distributed microcracks in the PO chondrules and the matrix assemblages, and (ii) the nucleation of macrocracks near the PP chondrules and FeNi-metal nodules. In this context, one would also expect that the smaller fractured fragments are composed of olivine minerals, while the larger ones contain the remains of the PP chondrules and FeNi-metal nodules along the crack path (near the edges of these fragments).

This hypothesis is confirmed by the µCT images since the content of the PP-rich textures and droplets of metal in small fragments is low (Figs. 8d–f), as compared to the larger ones. It is speculated that these pieces of metallic debris in the small fragments originated from the PO chondrules (e.g., the top-right chondrule in Fig. 3b) and/or from the precursor material (e.g., well defined metal spheroids between the chondrules in Fig. 3a). Figures 8b–c show many medium- and large-sized fragments populated with the PP chondrules and FeNi-metal nodules (indicated by the white arrows). Interestingly, most of these microstructural phases remained intact, including those observed on the crack paths (see magnified fragments in Fig. 8b–c). This is especially true for the FeNi-metal nodules, which show better resistance to cracking as compared to the olivine crystals. Such a combination of constituent properties in the material (i.e., metallic phases which exhibit good ductility and rather brittle mineral matrix) must lead to stress concentrations and subsequent crack nucleation at the metal/olivine interface under applied compressive loading conditions. Thus, the content of FeNi-metal nodules, although low, is ultimately responsible for the catastrophic failure of the chondrite structure. These results, considered together, suggest the presence of two fragmentation mechanisms under the investigated loading conditions, namely the microstructure- and structure-dependent fragmentation.

Microstructure-dependent (MD) fragmentation is associated with the length scales of microstructural features, such as the spacing between primary phases in chondrules (e.g., olivine minerals, FeNi-metal nodules) or pre-existing defects (microcracks and pores) (Hogan et al., 2015b, 2016). That is to say, the resulting average fragment size at this length scale roughly corresponds to the average spacing between the critical-size microstructural features. However, each microstructural feature has a different propensity to act as a crack nucleation site which depends upon its unique characteristics (e.g., size, shape, orientation, properties, etc.), as well as the loading conditions (i.e., strain rate and stress state). For example, low rates of loading would activate cracks from larger defects like FeNi-metal nodules (thus produce fragment sizes associated with the spacing between those defects), while the more extreme loading conditions can lead to smaller length scales (activate cracks from defects of different sizes) and result in smaller fragment sizes (Li et al., 2018; Rae et al., 2019; Zhang et al., 2020; Daphalapurkar et al., 2011; Cereceda et al., 2017).

The second mechanism of fragmentation, referred to as structure-dependent (SD) fragmentation, is associated with the macroscopic failure of the specimen as observed in Figure 5 (Hogan et al., 2015b, 2016). In this case, the resulting fragment number, shapes and sizes are the consequence of coalescence of axial and transverse cracks governed by the geometry of the specimen and applied loading conditions. As shown in radiographs 6–8 in Fig. 5a, the coalescence of macroscopic cracks from the metal/olivine interfaces led to the formation of column-like fragments, which were further reduced to smaller fragments due to subsequent buckling. Note that the largest fragments (Fig. 8b) appear to have a higher aspect ratio than the medium-size fragments (Fig. 8c), which were likely the column-like fragments reduced in the final stage of loading.

These fragmentation mechanisms can further be discussed and understood in this complex multi-phase material by plotting the sphericity of the fragments against their size. The fragment size is defined by the largest side length of a smallest bounding box encompassing the fragment, while the sphericity, ψ, was calculated as,

$$\psi = \left(\frac{9}{2}\pi\right)^{1/3} \frac{(mn)^{2/3}}{mn+m+n} \approx \frac{2.418(mn)^{2/3}}{mn+m+n}, \tag{1}$$

where, $m = b/a$ and $n = c/a$ (Li et al., 2012). The parameters a, b and c are the side lengths of the smallest bounding box encompassing the fragment. Thus, the maximum value of sphericity was measured when the bounding box of the fragment becomes a cube ($m = n = 1$), which gives $\psi_{max} = (\pi/6)^{1/3} \approx 0.806$. This approach was used to analyse ~11430 fragments from three µCT investigations (an average of 3810 ±612 fragments per specimen) resulting in the scatter plots shown in Fig. 9 and 10. However, due to the large dataset involved, the scatter plot information were transformed into a grid, and the number of data points on each position of the grid was counted and represented by a graduating colour. Such a graphical representation prevents overplotting of data points and can help to identify hidden patterns in the population of fragments.

Figure 9 shows the sphericity of the fragments against their size, where the colour corresponds to the number density of each bin (i.e.: the number of observations within a particular area of the xy–plane). Two characteristic peak densities can be identified in this figure. The first peak is associated with the population of smallest-size fragments (representing microstructure-dominated fragmentation and indicated as 'MD1' in Fig. 9) and has a very strong density representation. The sphericity and fragment size of the peak density is ∼0.78 and ∼70 µm, respectively. However, the sphericity numbers in this group are spread out from the peak value, and the average fragment size is slightly larger (∼85 µm). These characteristics (i.e., irregular to blocky shapes of the fragments) are relevant to the fragments that originated from the PO chondrules and the fine-grained matrix of similar composition, as shown in Fig. 2a–e. Consequently, these microstructural features can produce very fine debris and fragments even in low-velocity impact scenarios. The total number of fragments within this group was estimated to be ∼7000, representing ∼60% of the entire population. Figure 9 also shows the fragment size distribution, where the y-axis is the normalised count of the number of fragments of a given size.

The second population of fragments (also associated with the microstructure-dominated fragmentation and indicated as 'MD2' in Fig. 9) has much weaker, but perceptible, density representation. The peak density corresponds to the sphericity of ∼0.79 and the fragment size of ∼160 µm. Interestingly, many fragments of this characteristic size and shape were observed to contain the fragments of PP chondrules and FeNi-metal nodules, as shown in the magnified views of the fragments in Fig. 8c. Note that the average fragment size in this population of fragments corresponds to the average spacing between the FeNi-metal nodules (Fig. 7). It is believed that these microstructural features are associated with the population of fragments concentrated near the peak density of 'MD2'. It should be noted that similar relationships were found between the spacing of the FeNi-metal nodules and the fragment sizes in the L-type chondrite of the petrologic type 6 by Hogan *et al.* (Hogan et al., 2015c). The total number of fragments associated with the peak density is small, but as shown in Fig. 10, their volume fraction significantly contribute to the microstructure-depended fragmentation (colour in Fig. 10 corresponds to the volume fraction contribution of each bin). Note that the volume distribution is rather uniform for the fragment size of 70–500 µm, and concentrated within the sphericity number of 0.79±0.01. Figure 10 also shows the normalised cumulative volume distribution of fragment sizes. Note the transition point ∼800 µm, which indicates the change in fragmentation mechanism. That is to say, the fragments smaller than ∼800 µm are likely associated with the microstructure-dependent fragmentation, while the larger ones originate from the structural collapse of the specimen. The fragments concentrated within the last fragment population represents the structure-dominated fragmentation and are indicated as 'SD' in the scatter plot (the data in grey colour is out of scale range, i.e., >0.06). These are the largest fragments that resulted from the buckling and fracture of column-like fragments during the final stage of loading.

6. Discussion

6.1. Compressive Strength of Chondrites

The results of this study shows how the mechanical response of stony meteorites to dynamic compressive loading can be linked to the microstructure and its morphology. By and large, the FeNi-metal nodules played an important role in this process, since the presence of larger inclusions resulted in substantial reduction in compressive strength and their distribution affected the fragmentation processes. Note that metal is present in a vast majority of stony meteorites, but its concentration varies for each sub-class of chondrites. For example, the most common H-type chondrites (45% of all classified chondrites (Davis, 2005)) contain ∼8 vol% metal by volume in the form of irregular grains (outside and inside of chondrules), metal nodules, veins, or metal oxides. The average metal grain size in the H-type chondrites is on the order of 200 µm. The presence of metallic compounds in the L-type chondrites (40% of all classified chondrites) is of the order of 3 vol.%, and the average metal grain size is about 180 µm. The last group of chondrites, the LL-type chondrites, have the least metal among all stony meteorites, for which a metal content of 1.5 vol.% is frequently reported (Davis, 2005). This group of chondrites also has the smallest metal grain size (140 µm).

To date, only a handful of studies of the compressive strength of stony meteorites exist (Buddhue, 1942; Baldwin and Sheaffer, 1971; Tsvetkov and Skripnik, 1991; Miura et al., 2008; Slyuta et al., 2009; Kimberley and Ramesh, 2011b; Hogan et al., 2015c; Slyuta, 2017). Unfortunately, comparison between the results is made difficult due to lack of details about the experiment (e.g., the specimen geometry or mass) and the meteorite itself (e.g., the degree of weathering, shock stage or porosity). Moreover, the reported strength values are often based on a handful of experiments performed in compression under quasi-static loading conditions. Currently, there is a limited amount of data concerning the dynamic loading conditions (Kimberley and Ramesh, 2011b; Hogan et al., 2015c). The data found in the literature and the results of this study are plotted against the amount of metal compounds in different groups of chondrites, and the average metal grain size in Fig. 11. It should be cautioned that there are limited studies examining the characteristics of the FeNi-metal nodules in these meteorites, and so the metal content should be treated as rough estimates.

First, there is no significant trend in the average strength of the three types of chondrite with increasing metal content or mean metal grain size in the quasi-static strain rate regime. That is to say, the average compressive strength of the H-type chondrites is about 201±86 MPa, while the L-type chondrites show a slightly lower strength value (186±117 MPa) as compared to the iron-rich counterparts. In the case of the LL-type chondrite, there is not enough data to draw any valid conclusions. Another observation is that the L-type chondrites that experienced different degrees of alteration by terrestrial processes show different responses to loading. For example, the L-type chondrites of the petrologic type 3–5 seem to have higher strengths than the chondrites that have been metamorphosed under conditions sufficient to homogenise all mineral compositions (i.e., Type 6–7). Thus, there is an apparent effect of thermal metamorphism on the physical and mechanical properties of the L-type chondrites. Also, the average strength of the L3–6 type chondrites (251±129 MPa) is noticeably higher than the average strength of the H-type chondrites. This is likely due to the fact that the H-type chondrites contain higher abundance of metal, often present in large assemblages as compared to the other chondrite groups.

The spread in measured compressive strength values in each group is perceptible. This suggests that factors other than FeNi-metal compounds have an influence on the mechanical behaviour of chondrites. For example, as suggested in this study (Fig. 6), the presence of higher porosity might also result in perceptible reduction in compressive strength. This appears to be a general trend in each group of chondrites (the bulk porosity and the shock stage for chondrites with known properties are reported in Fig. 11). Also, many of the studied meteorites have experienced significant terrestrial weathering, which transformed original minerals to alteration products (e.g., oxidation of metal, replacement of silicates by clay minerals and oxides). The mechanism of failure initiation is therefore very complex and difficult to generalise from these studies. A better knowledge about the material characteristics and the specimens' morphology is necessary to draw further conclusions.

Finally, a strong strain rate dependence of compressive strength was observed in the previous studies (Kimberley and Ramesh, 2011b; Hogan et al., 2015c). For example, the strength of the L-type chondrites of petrologic types 5–6 was found to increase by a factor of 3.5 (Hogan et al., 2015c) and ∼4 (Kimberley and Ramesh, 2011b) between the quasi-static and dynamic regimes (strain rates of $10^2 - 10^3$ /s). The average dynamic compressive strength of the chondrite investigated herein is ∼3 times higher than the average strength value of all stony meteorites in the L group. These results are not surprising given that terrestrial basalts show similar response when subjected to dynamic compressive loading (Lindholm et al., 1974; Stickle et al., 2013). Boundary regions of compressive strength of basaltic rock studied by Stickle *et al.* (Stickle et al., 2013) are projected in Fig. 11. The strain rate dependence of the compressive strength was also observed in the case of other geological materials (Kumar, 1968; Green and Perkins, 1969; Frew et al., 2001). The rate effects, therefore, are important and add complexity to the dynamic/impact problems.

6.2. Fragmentation

Predictions of size distribution or fragment number in the dynamic fragmentation process are very challenging as they require a comprehensive analysis of loading conditions, material characteristics and geometry. To date, many approaches have been proposed to solve the fragmentation problem, such as the pioneering studies by Lienau (Lienau, 1936) and Mott (Mott and Linfoot, 1943), predictions that use energy criteria (Grady, 1982; Glenn and Chudnovsky, 1986), a fracture mechanics approach (Glenn et al., 1986) or, most recently, predictions based on numerical simulations (Xu and Needleman, 1994, 1996; Camacho and Ortiz, 1996; Espinosa et al., 1998; Miller et al., 1999; Zhou et al., 2006a,b; Levy and Molinari, 2010). By and large, these models provide simplified formulae to estimate the average fragment size rather than the fragment size distribution. For example, the model proposed by Grady (Grady, 1982) offers a solution for the average fragment size, s, that can be expressed in the following non-dimensional form:

$$\overline{s} \equiv \frac{s}{s_0} = \left(\frac{24}{\overline{\dot{\epsilon}}^2}\right)^{1/3}, \tag{2}$$

where $\overline{s}$ is the average fragment size normalised by the characteristic fragment size, s_0, and $\overline{\dot{\epsilon}}$ is the strain rate ($\dot{\epsilon}$) normalised by the characteristic strain rate, $\dot{\epsilon}_0$. The characteristic fragment size and the characteristic strain rate are given by:

$$s_0 \equiv c t_0 = \frac{E G_c}{\sigma_t^2}, \tag{3}$$

$$\dot{\epsilon}_0 \equiv \frac{\sigma_t}{E t_0} = \frac{c \sigma_t^3}{E^2 G_c}, \tag{4}$$

where c is the longitudinal speed of sound in the material, t_0 is the characteristic time, E is the Young's modulus, σ_t is the quasi-static tensile strength of the material, and G_c is the fracture energy under plane stress conditions equivalent to

$$G_c \equiv \frac{K_{Ic}^2}{2E}, \tag{5}$$

where K_{Ic} is the fracture toughness.

The characteristic fragment size (s_0), the characteristic strain rate ($\dot{\epsilon}_0$), and the characteristic time (t_0) can also be used to normalise the average fragment size proposed in other brittle fragmentation models. For example, the normalised average fragment size defined by Glenn and Chudnovsky (Glenn and Chudnovsky, 1986) can be defined as:

$$\bar{s} = \frac{4}{\bar{\dot{\epsilon}}} \sinh\left(\frac{1}{3}\sinh^{-1}\left(\frac{3}{2}\bar{\dot{\epsilon}}\right)\right). \tag{6}$$

This analytical model is based on similar principles as the Grady's model (Grady, 1982). That is, both assume that the high strain-rate domain is controlled by the local kinetic energy term and provide the prediction of decreasing fragment size with increasing strain rate. Glenn and Chudnovsky (Glenn and Chudnovsky, 1986), however, introduced an additional term accounting for the stored elastic energy before failure, which in turns made the fragment size independent of strain rate in the low strain-rate domain.

Similarly, the normalised average fragment size defined by Zhou et al. (Zhou et al., 2006a,b) can be expressed as:

$$\bar{s} = \frac{4.5}{1 + 4.5\bar{\dot{\epsilon}}^{2/3}}, \tag{7}$$

and for Levy and Molinari (Levy and Molinari, 2010) this term is given by:

$$\bar{s} = \frac{3}{1 + 4.5\bar{\dot{\epsilon}}^{2/3}}. \tag{8}$$

Both studies evolved from the aforementioned analytical approaches and provide numerical solutions to characterise the dynamic brittle fragmentation processes. As Zhou et al. (Zhou et al., 2006a,b) developed a crack initiation criterion and a cohesive crack growth model, the work of Levy and Molinari (Levy and Molinari, 2010) extended this approach by including defect distributions. It should be noted that all these studies ((Grady, 1982; Glenn and Chudnovsky, 1986; Zhou et al., 2006a,b; Levy and Molinari, 2010)) provide an estimate of the average fragment size under tensile loading, and so the comparison with the dynamic compression experiments presented herein cannot be made directly. That is to say, the strain rate under tensile conditions needs to be defined in order to compare the experimental fragment sizes with the theoretical predictions. Recently, Hogan *et al.* (Hogan et al., 2016) in their work on compressive brittle fragmentation approached this problem by defining an equivalent expanding ring problem, where the equivalent tensile strain rate ($\dot{\epsilon}_{eq}$) from a compressive loading experiments was approximated as

$$\dot{\epsilon}_{eq} = \frac{\upsilon_{ring}}{r} = \sqrt{\frac{\sigma_c^2}{\rho E r^2}}, \tag{9}$$

where r is the equivalent expanding ring radius (equals or exceeds ten times of the specimen length), υ_{ring} is the velocity of the expansion of the equivalent expanding ring, σ_c is the compressive strength, and ρ is the density of the material. The above derivation is based on the assumption that the strain energy in compression is equal to the kinetic energy of an expanding ring.

Figure 12a shows a comparison between the theoretical predictions of the models, the experimental results of this study, and the data presented elsewhere (Hogan et al., 2016; Wang and Ramesh, 2004; Bakas et al., 2012; Hogan et al., 2015b; Kimberley and Ramesh, 2011a; Stickle et al., 2013; Balme et al., 2004; Hogan et al., 2015a, 2014, 2015c). The values of the parameters used to generate data for this study and the models are listed in Tab. 1. It should be noted that the experimental data are for various brittle materials and based on compressive experiments performed on the specimens having similar sizes. This is motivated by the fact that the measurements of the tensile strength of brittle materials show a broad scattering and there are many technical challenges associated with such testing (i.e., a direct tensile test is not suitable for brittle materials). On the other hand, different specimen sizes can yield different results for dynamic strength and fragmentation (the fracture strength of rocky bodies is known to be both size and time dependent (Housen and Holsapple, 1999)). To date, there is still limited data on the tensile strength of stony meteorites. Thus, this value is approximated as $\sigma_t = \sigma_c/10$, which is based on the trends and reference values for brittle materials reported in the literature (Charles, 2001; Wachtman et al., 2009). The quasi-static compressive strength is approximately one-third of the dynamic compressive strength, which corresponds to the average strength value of all stony meteorites in the L group and is in line with the observed strain rate dependence of compressive strength of the L-type chondrites (Kimberley and Ramesh, 2011b; Hogan et al., 2015c). K_{Ic} value is based on the fracture toughness measurements on igneous rocks due to the lack of data (Balme et al., 2004). All other values are based on the measurements collected on the investigated chondrite (or calculated from these measurements). The uncertainties in experimental data that are plotted on a graph reflect the combined uncertainties associated with the properties of these rocks and ceramics, which are as follow: ±20% in σ_t (based on the results presented in Ref. (Charles, 2001)), ±5% in E, ±5% in ρ, ±5% in c, ±40% in K_{Ic} for rocks and ±20% in K_{Ic} for ceramics. Thus, the error bars in Fig. 12a represent lower and upper bounds for the characteristic terms assuming various uncertainties for the mechanical properties.

c_L (m/s)	c_S (m/s)	ρ kg/m^3	E (GPa)	$\sigma_{c,dyn}$ (MPa)	σ_c (MPa)	σ_t (MPa)	K_{Ic} $(MPa\sqrt{m})$	s (μm)
$5685^{(1)}$	$3684^{(1)}$	$2740^{(1)}$	$84.6^{(2)}$	$578^{(1)}$	$192^{(3)}$	$19.2^{(4)}$	$1.6^{(5)}$	$1200^{(1)}$

Table 1: Model parameters, where: (1) measured value, (2) calculated based on the density and ultrasound measurements, (3) $\sigma_{c,dyn}/3$ – approximated based on the average strength value of all stony meteorites in the L group, (4) $\sigma_c/10$ – approximated based on the trends and reference values for brittle materials (Charles, 2001; Wachtman et al., 2009), (5) approximated based on the fracture toughness measurements on igneous rocks (Balme et al., 2004).

Based on the comparison between theoretical predictions with available data sets in Fig. 12a, it can be concluded that most of these models can provide good agreement with experimental compressive fragmentation studies. This is especially true for 'man-made' materials and brittle materials with rather homogeneous density of defects. The predictions of the average fragment size for igneous rocks and stony meteorites tend to be over-predicted, which can be attributed to the complex and rather imperfect microstructures preserved in rocks. As a matter of fact, such knowledge is not taken into account in these predictive models. However, a good agreement is observed between the theoretical predictions of these models and experimental data collected in this study.

In the figure, the data and the models are presented along with results from a modelling study of three impacts events, in which a sphere collides with a target at 5 km/s and with the impact direction normal to the target surface (as shown in the figure inset, Fig. 12b). In the study, both objects were made of quartz, and the sphere diameters were 1 cm, 1 m and 1 km. For further details the reader is referred to the original paper (Ernst et al., 2009). The strain rate domains of these impact events are normalised strain rate values experienced by the bulk of the target (not by the impacted domain). Hence, two observations can be made based on these results. First, in case of the small-scale impact simulations (1 cm diameter sphere), the bulk of the target experienced strain rates that are similar to the laboratory experiments. Second, the simulations of the planetary impact scenarios (1 km diameter sphere) suggest the presence of much lower strain rates as compared to the laboratory-scale impacts. It is therefore important to choose a model that can both accurately capture the fragmentation in the laboratory-scale experiments, and also generalise well across different length scales. For example, the average fragment size provided by the model proposed by Grady (Eq. 2) can be overestimated in the planetary-scale size regime by one or two orders of magnitude. On the other hand, it is difficult to identify the model that addresses planetary fragmentation problems with great accuracy since the scaling laws used in these models cannot be verified experimentally. Nonetheless, in the case of stony meteorites with limited data available, these models can provide useful information about impact-induced fragmentation processes that have helped shape the current solar system.

7. Summary

A split-Hopkinson pressure bar technique and synchrotron phase-contrast X-ray radiography at the European Synchrotron Radiation Facility (ESRF) was used to investigate *in-situ* the subsurface dynamics of an L-type ordinary chondrite during dynamic compression. Synchrotron X-ray microtomography (µCT) provided supplementary characterisation of chondrules present in the specimens and post-test examinations of collected fragments. The resulting data were then used as material parameters in analytical models for fragmentation of brittle materials. The experimentally observed dynamic fragmentation processes of different brittle materials investigated under similar dynamic loading conditions were compared against the theoretical predictions of dominant fragment size during fragmentation. Consequently, the following conclusions were made from these results:

(1) The damage in dynamically compressed specimens was initiated in close proximity to the FeNi-metal nodules, which acted as preferential sites for the nucleation of the very first cracks. The cracks propagated across the porphyritic olivine and porphyritic pyroxene type chondrules in a transgranular manner and along the loading direction, which led to the formation of column-like fragments.

(2) The µCT analysis of the collected fragments showed that the population of the FeNi-metal nodules was important to the failure and fragmentation processes, and led to the formation of fragments having sizes corresponding to the characteristic length-scales (spacing) between the FeNi-metal nodules. The population of smaller debris fragments was associated with the porphyritic olivine chondrules and the matrix material.

(3) For laboratory-scale experiments, it was demonstrated that the models tend to over-predict the average fragment size for terrestrial rocks and meteorites, and found to be in good agreement for man-made materials. This can be related to the complex and heterogeneous microstructure preserved in meteorites and rocks, as opposed to ceramics. But what is more important is that through this combined experimental and analytical approach it was possible to

explore the characteristic fragments sizes at strain rates that are relevant for planetary-scale dynamic events, such as collisions between asteroids (or asteroids with planets), or asteroids colliding with projectiles.

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Figure 1. Picture of the investigated L-type ordinary chondrite (NWA 5477), which was classified as an L3.2 chondrite, weakly shocked (shock stage of S2), and with little or no weathering (weathering grade of W1). The section cut contains large and well-defined chondrules of various petrological types in fine-grained matrix assemblages.

Figure 2. Synchrotron X-ray µCT images of the common chondrules: (a–b) the PO chondrules composed of olivine crystals immersed in a homogeneous mesostatis and the pre-existing microcracks indicated by the white arrows; (c) the PP chondrules associated with pyroxene and abundant FeNi-metal nodules; (d) the POP chondrules occupied by olivine grains and surrounded by rims of pyroxene (indicated by the white arrow) and FeNi-metal aggregates (indicated by the black arrow); (e) the PO chondrules showing some evidence for rapid quenching/cooling at the early stage of chondrite formation.

Figure 3.: Schematic diagram of the high strain rate compression experiment at ESRF-ID19, showing (a) a cuboid meteorite specimen in the split-Hopkinson pressure bar (SHPB) test, and (b) image acquisition system. The ESRF storage ring operated in 16-bunch filling mode. Synchrotron phase-contrast X-ray radiography was performed transverse to the compression direction, and approximately 145 m away from the synchrotron radiation source. Synchronisation of the SHPB system and the source was achieved by the X-ray bunch clock and the signal from a strain gauge located on the incident bar. The incident X-ray photons were absorbed by a LYSO:Ce scintillator and recorded by high-speed cameras.

Figure 4.: (a) Schematic illustration of the specimen and loading arrangement in the dynamic compression experiment. Dashed lines indicate locations of X-ray virtual µCT slices (shown as Images 2–4 in Fig. 5c); (b) stress-time history

resulting from the dynamic compression experiment with highlighted times of the X-ray images (light blue- and purple-filled circles for camera 1 and 2, respectively).

Figure 5.: (a) Series of time correlated radiographs captured during the dynamic compression experiments presented in Fig. 4; (b) waterfall plots of the normalised pixel intensities along the paths indicated in Radiograph 1 in Fig. 5a; (c) µCT images of the specimen acquired before the dynamic test, where: Image (I) is a high-resolution transmission image generated as an average image of all µCT slices along the X-ray beam direction, and Images (II–IV) are the µCT slices of the specimen at locations indicated in Fig. 4a. Highlighted areas of radiographs 2-3 in Fig. 5a corresponds to highlighted areas of Image 1 in Fig 5c.

Figure 6.: Measured peak stress values against the volume fraction of: (top) the PP chondrules; (middle) FeNi-metal nodules; (bottom) porosity. The black dashed line represents the trend in the experimental results, while the grey dashed line represents the average peak stress value ($< \sigma_p >$) for all tests. R^2 is the coefficient of determination indicating the goodness of curve fitting.

Figure 7. Effect of size and spacing of FeNi-metal nodules on the peak strength, where: $\mathrm{D_{max}}$ is the size of the largest FeNi-metal nodule (top), $\mathrm{D_{mean}}$ is the mean size of the FeNi-metal nodules (middle), and $\mathrm{L_{mean}}$ is the mean distance between FeNi-metal nodules in the specimen (bottom). The black dashed line represents the trend in the experimental results, while the grey dashed line represents the average peak stress value ($< \sigma_p >$) for all tests. R^2 is the coefficient of determination indicating the goodness of curve fitting.

Figure 8.: (a) Schematic illustration of the conical polypropylene tube containing fragments of the specimen with superimposed contours of longitudinal and transverse cross-sections of the tube; (b–f) µCT images of the cross-sections

indicated in schematic (a) showing fragments of different sizes. White arrows in subfigures (b–c) indicate FeNi-metal nodules.

Figure 9. Scatter plot of the sphericity of the fragments against their size. The colour corresponds to the number density of each bin. MD1 and MD2 are the two characteristic microstructure-dependent fragmentation populations. The top subfigure shows the fragment size distribution, where the y-axis is the normalised count of the number of fragments of a given size.

Figure 10. Scatter plot of the sphericity of the fragments against their size. The colour corresponds to the volume fraction contribution of each bin. MD1 and MD2 are the two characteristic microstructure-dependent fragmentation populations, and SD is the structure-dependent fragmentation population. The top subfigure shows the fragment size distribution, where y-axis is the normalised cumulative volume distribution of fragment sizes.

Figure 11.: The compressive stress values of different stony meteorites (Buddhue, 1942; Baldwin and Sheaffer, 1971; Tsvetkov and Skripnik, 1991; Miura et al., 2008; Slyuta et al., 2009; Kimberley and Ramesh, 2011b; Hogan et al., 2015c; Slyuta, 2017) plotted against the average metal grain size and the amount of metal compounds (rough estimates) in the corresponding sub-class of chondrites (Davis, 2005). The results of dynamic compression tests are represented by filled star symbols. All other data are quasi-static compression tests. Yellow bars indicate boundary regions of compressive strength of terrestrial basalt (Stickle et al., 2013). A comparison within the sub-class of chondrites can be made based on the shock stage and reported porosity values.

Figure 12.: (a) Comparison of normalised average experimental fragment sizes observed in this study (in green) and elsewhere (Hogan et al., 2016; Wang and Ramesh, 2004; Bakas et al., 2012; Hogan et al., 2015b; Kimberley and Ramesh, 2011a; Stickle et al., 2013; Balme et al., 2004; Hogan et al., 2015a, 2014, 2015c)

with the theoretical predictions of the models (Grady, 1982; Glenn and Chudnovsky, 1986; Zhou et al., 2006a,b; Levy and Molinari, 2010). The error bars represents minimum and maximum values for the characteristic size and the normalised strain rate based on all possible combinations of uncertainties. The figure also shows the normalised characteristic strain rate regimes present in small-, intermediate- and planetary-scale impact events (Ernst et al., 2009); (b) Schematic representation of the simulated impact events that were used in approximations of the normalised characteristic strain rate regimes.