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Experiments on the consolidation of chondrites and the formation of dense rims around chondrules

E. Beitz [a,*], C. Güttler [b,a], A.M. Nakamura [b], A. Tsuchiyama [c], J. Blum [a]

[a] Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstr. 3, D-38106 Braunschweig, Germany
[b] Department of Earth and Planetary Sciences, Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan
[c] Division of Earth and Planetary Sciences, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

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ABSTRACT

We performed impact experiments into mixtures of chondrule analogs and different dust materials to determine the dynamic-pressure range under which these can be compacted to achieve porosities found in chondritic meteorites. The second objective of our study was to test whether or not fine-grained dust rims around chondrules can be formed due to the dynamic compaction process. In our experiments, aluminum cylinders were used as projectiles to compact the chondrite-analog samples in a velocity range between 165 m s^{-1} and 1200 m s^{-1}. The resulting impact pressures in the samples fall between ∼90 and ∼2400 MPa. To measure the achieved porosities of our samples, 25 samples were analyzed using computer-aided tomography. We found volume filling factors (porosities) between ϕ = 0.70 (30%) and ϕ = 0.99 (1%) which covers the observed range of volume filling factors of carbonaceous chondrites (CC) and ordinary chondrites (OC). From our experiments, we expect CM chondrites to be likely compacted in a pressure range between 60 and 150 MPa, CV chondrites appear to be compacted with pressures between 100 and 500 MPa, and for OCs we only determined a lower limit of the compaction pressure of 150 MPa. These dynamic compaction pressures are in good agreement with the typical shock stages of the chondrites, and thus can confirm that CM chondrites are less shocked than CV chondrites and significantly less shocked than OCs. Finally, we found a factor of 10 difference in the dynamic-pressure compaction range of CCs and OCs that allows us to infer either a larger distance between the formation location of the two chondrite families than current models predict or a strong difference in orbital eccentricities for the two groups. As for the high-density rims found around chondrules, we can show that these do not form in dynamic compaction processes as studied in this paper.

1. Introduction

Chondritic meteorites are the largest fraction of all meteorites making up more than 85% of the meteorites in our collections (Bischoff and Geiger, 1995). Age determination done by Amelin et al. (2002) has shown that the mm-sized spherical constituents, the chondrules, are only ∼2.5 Myr younger than the Ca- and Al-rich inclusions (CAIs), which are the first condensates of the Solar System. Because of their ubiquity and their formation time, the chondrites seem to be tightly connected to the coagulation phase of planetesimals whose formation conditions remain relatively unclear. The chondrules are making up between 0 and 80 vol.% of the chondrites and, thus, constitute one of their major fractions (Hewins et al., 2005). Other important constituents of chondrites are the matrix (0–100 vol.%), the opaque phases (0–70 vol.%), and the CAIs (0–3 vol.%) (Brearley and Jones, 1998; Zanda, 2004; Hezel et al., 2008; McSween, 1977).

Beitz et al. (2012b) have shown in laboratory experiments that chondrules covered with a thin dust rim tend to form large clusters very rapidly. Such a fast and/or local accretion process is in good agreement with the material complementarity of the chondrules, the dust rims, and the matrix, as reported in Palme et al. (1993). Beitz et al. (2012a) showed that a parent body formed by coagulation of chondrules and matrix material, while freely floating in the solar nebula, possesses a porosity which depends on its matrix fraction. However, the expected volume filling factors ϕ (defined as 1-porosity) are not consistent with values found in carbonaceous chondrites, which cover a range between ϕ = 0.58 and ϕ = 1.0 (Macke et al., 2011). Thus, Beitz et al. (2012a) concluded that additional compaction of the chondrite parent bodies is required.

Such a compaction process was suggested earlier by Trigo-Rodriguez et al. (2006) to explain the formation of high-density dust rims around chondrules that are found in several types of carbonaceous chondrites. The CM chondrites are famous for these

* Corresponding author.
E-mail address: e.beitz@tu-bs.de (E. Beitz).

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fine-grained rims and all larger meteoritic constituents are surrounded by dust rims. Metzler et al. (1992) investigated the typical relation between the rim thickness and the chondrule diameter and found a linear relation with typical rim thickness of about 20% of the chondrule diameter. These fine-grained rims are typically denser than the surrounding matrix. This was investigated by Beitz et al. (2012a) for a fine-grained rim surrounding a chondrule in the CM2 chondrite Murchison using computer-aided tomography. They found a volume filling factor of the rim higher by $\Delta\phi = 0.1$ compared to the overall value of the Murchison chondrite ($\phi = 0.78$, measured by Macke et al. (2011)). This enhanced (packing) density around the chondrule is in good agreement with the rim densities measured by Wilson et al. (1999) and also in the range of the rim volume filling factors of $\phi = 0.90–0.94$ measured by Wasson (1995).

The aim of this new study is to investigate the degree of compaction and maximally achievable volume filling factor of different dust and chondrule-analog mixtures in a dynamic compaction process and to prove or disprove the formation of fine-grained overdense rims around the chondrules. High-velocity collisions occurred regularly during the planetesimal-formation process so that their impact on the porosity evolution of the growing planetesimals is interesting to study. Furthermore, we intend to derive the dynamic-pressure range in which such chondrule and dust mixtures were compacted and consolidated in the solar nebula to obtain the typical collisions velocities and constrain the processes responsible for the formation of planetesimals.

2. Experimental technique

We performed impact experiments with the basic idea to dynamically compress a cylindrical chondrule-dust sample of 2 cm diameter and up to 10 cm length by use of a fast aluminum projectile. The samples consisted of a mixture of micrometer-sized dust particles (as matrix analogs) and millimeter-sized solid beads (as chondrule analogs) and were aimed to represent a pre-chondrite body, i.e. a growing planetesimal. The cylindrical aluminum projectiles were accelerated in a powder gun to velocities of up to 1200 m s^{-1} and dynamically compressed the target to a sturdy, sandstone-like sample in most cases. The consolidated samples were recovered after the impact experiment and were then further analyzed by computer-aided X-ray tomography.

2.1. Impact-compression experiments

We used a vertical powder gun at Kobe University, which has been described in detail by Kani and Yamada (1984) and which is shown in Fig. 1a. An aluminum cylinder (projectile) of 1.48 cm diameter and 3 or 5 cm length, respectively, was accelerated by a powder explosion with which a maximum velocity of 1200 m s^{-1} could be achieved. The minimum velocity generated in this study was 165 m s^{-1}. As target samples, we prepared mixtures of dust powders and solid beads of different materials and mixing ratios. The samples were placed into in nylon cylinders of 2 cm inner diameter, 10 cm length and a wall thickness of 2.5 mm, and were covered with 0.1 mm thick aluminum plates to seal them from contamination (e.g., by gunpowder). Due to the enormous impact energy, the nylon cylinders were placed in a steel housing, which is shown in Fig. 1b. The nylon tubes were first mantled with six inner steel brackets (each 5 cm in length and covering 1/3 of the circumference) and this inner housing was fixed with three pairs of outer steel brackets, held together by screws. After the sixth shot (out of 46), two of these screws burst so that we added a steel tube as a third shell, as can be seen in Fig. 1b.

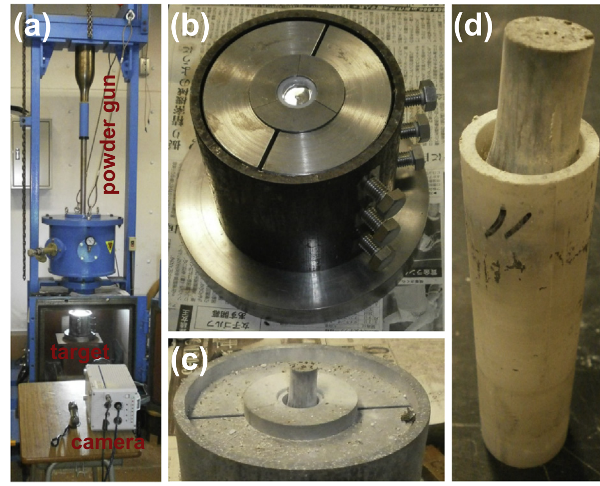

Fig. 1. Photographs of the powder gun and the target. (a) Powder gun with high-speed camera and target in the vacuum chamber. (b) Target before impact. (c) Target after impact with projectile sticking out. (d) Recovered sample inside a 20 mm (inner) diameter nylon tube.

The target and its mounting were assembled and placed inside a vacuum chamber. The barrel of the powder gun was then manually centered over the sample with a rod so that the 1.48 cm diameter projectile preferentially hit the center of the 2 cm diameter target. An alignment precision of 1–2 mm between the centers of projectile and target was achieved so that in the shots presented in this paper, the projectile never hit the nylon tube. The gun was fired after pumping down the vacuum chamber to a pressure below 50 mbar. The velocity of the projectile was pre-determined by the amount of gunpowder used in the setup, but this method possesses a significant uncertainty. We therefore also measured the impact velocity with a high-speed camera operated at 100,000 frames per second and back-light illumination (see Fig. 1a).

2.2. Sample preparation

To simulate the impact consolidation of chondritic planetesimals in an experiment, proper analog material is required. As chondrules show many different crystallization types, like olivine, pyroxene or glassy structures, their tensile strength can also vary over some orders of magnitude. Unfortunately, we are not aware of any tensile strength measurements on real chondrules. Thus, we used three different chondrule analog materials to cover the wide range of possible tensile strengths. For weak chondrules, we used soda-lime glass with a tensile strength of 33 MPa (manufacturer: Hilgenberg), for intermediate tensile strengths of 48 MPa, we used SiO_2 beads (manufacturer: Hilgenberg), and alumina (Al_2O_3) spheres were used to simulate very resistant chondrules with a tensile strength of 267 MPa (manufacturer: Goodfellow). The diameter of these chondrule analogs was always around 2 mm. The three materials also differ in their densities, with values of 2.52 g cm^{-3} (soda-lime glass), 2.60 g cm^{-3} (SiO_2), and 3.94 g cm^{-3} (alumina), respectively. These material densities cover the same range of densities as measured for grain densities of chondrites (Britt and Consolmagno, 2004).

As matrix analogs, dust of two different materials was chosen. In most of the experiments, we used SiO_2 powder with irregular grains of a size range between 0.5 and 10 μm. The second matrix-analog material consisted of soda-lime glass beads of 100 μm or 400 μm diameter, respectively, which were chosen to test whether or not these large grains get pulverized in the exper-