Icarus 226 (2013) 111–118

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Collision of a chondrule with matrix: Relation between static strength of matrix and impact pressure

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ARTICLE INFO

Article history:
Received 10 December 2012
Revised 25 April 2013
Accepted 3 May 2013
Available online 15 May 2013

Keywords:
Impact processes
Meteorites
Planetesimals

ABSTRACT

Chondrites are one of the major groups of meteorites. They consist of spherical objects called chondrules, which are typically (sub-)millimeter-sized, and fine-grained matrix between the chondrules. There exists a variety of models on the formation of chondrules, most of which have in common that chondrules were formed at some local place in the protoplanetary disk and later incorporated into the planetesimals which then formed the chondrite parent bodies. However, it has not yet been fully investigated how and under which conditions chondrules coalesce with the matrix. In this experimental study, we assume that chondrules and matrix were formed at different places in the protoplanetary disk and subsequently collided with each other. For this, we investigated the relation between the bulk strength of agglomerates and the impact pressure, and the threshold velocity for a chondrule to be embedded into the matrix. We performed collision experiments using three different accelerators to achieve collision velocity from 0.2 to 300 m s^{-1}. We also carried out static strength measurements for silica agglomerates which were used as targets to investigate their mechanical properties, using a compressive-strength testing machine. Finally, we measured the elastic limits of the dust agglomerate from their compression (pressure–displacement) curves. We found three types of collision outcomes: bouncing, surface sticking and intrusion of the chondrule-analog projectile. Comparing the compressive strength of the target with the impact pressure, we found that intrusion occurs when the strength of the target is smaller than the impact pressure. On the other hand, bouncing occurs when the strength of the target is larger than the impact pressure. The minimum intrusion velocities of chondrules for targets with 50% and 75% porosity were determined to be 46 and 3 m s^{-1}, respectively.

1. Introduction

Chondrites are composed of typically (sub-)millimeter-sized spherical objects called chondrules and fine-grained matrix (Weisberg et al., 2006). Many laboratory analyses on chondrites have been performed measuring their formation ages, chemical and mineralogical composition, and isotopic ratios. It was found that chondrules were once molten in a high-temperature environment and then rapidly cooled down (Jones et al., 2000). In contrast to that, the matrix consists of irregular-shaped grains of which some have not experienced high temperature (Brearley and Jones, 1998).

There are three major models for chondrule formation, the x-wind model (Shu et al., 2001), the shock-wave model (e.g., Hood and Horanyi, 1991; Yasuda et al., 2009), and the lightning model (e.g., Pilipp et al., 1992; Güttler et al., 2008). These models have in common that chondrules were formed in confined regions within the protoplanetary disk and that many individual events are required to explain the amount of chondrules observed. Chondrules were formed a few million years after Calcium Aluminum Inclusions (CAIs) formation according to several date determinations (e.g., Russell et al., 2006). Connelly et al. (2012) however, suggest that the formation of chondrules and CAIs started to occur at the same period with their high-resolution chronology.

The volume fraction of chondrules in chondrites varies for the different chondritic types. For example, primitive CI chondrites include only very few chondrules (≪1 vol.%), whereas ordinary chondrites include as much as 60–80 vol.% of chondrules (Weisberg et al., 2006). As these chondritic types are believed to originate from different heliocentric distances, this indicates that also the chondrule number density in the protoplanetary disk varied with heliocentric distance. Chondrite parent bodies are assigned to some classes of asteroids from the comparison of their laboratory reflectance spectra with the observed reflectance spectra of the respective asteroids. The fact that the abundance of asteroid classes changes with heliocentric distance, as described in the following, indicates that the chondrite parent bodies had some radial distribution. S-class asteroids, thought to be the parent

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0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.05.006

bodies of ordinary chondrites, are found mainly around 2 AU, whereas C-class asteroids, parent bodies of carbonaceous chondrites, are found around 3 AU (Gradie and Tedesco, 1982). Nakamura et al. (2011) analyzed surface particles of Asteroid 25143 Itokawa, which is classified as an S-class asteroid and found that the mineralogy and mineral chemistry of these particles resemble thermally metamorphosed LL chondrites. It was thus shown analytically that an S-class asteroid is the parent body of ordinary chondrites.

It has not yet been understood how chondrules coalesce with matrix and form chondrite parent bodies. Many chondrules in chondrites are surrounded by dusty rims. This is one of the characteristic textures in chondrites. Chondrule rims consist of fine-grained material and have thicknesses between a few and several hundred micrometer (Kring, 1991). According to the measurements of chemical composition of rims, chondrules and refractory inclusions experienced late, coeval processing (Kring, 1991). There are two competing views about the origin of chondrule rims: nebular dust origin (e.g., Metzler et al., 1992) and parent body origin (e.g., Tomeoka and Tanimura, 2000).

Beitz et al. (2012) suggested that chondrite parent bodies could have formed from clusters of dust-rimmed chondrules based on low-velocity collision experiments using glass beads of 2 and 3 mm diameter, respectively, each coated with micrometer-sized silica particles such that the dust rim porosity was between 82% and 60%. They concluded this from their observed sticking efficiency in the collisions between the dust-coated particles which was considerably higher than in collisions between dust agglomerates or glass beads alone.

Collision velocities between mm-sized aggregates and cm-sized aggregates in a protoplanetary disk are assumed to range from 1 to 30 m s^{-1} (Weidling et al., 2009), depending on the surface density of the disk. Droplets, as precursors of chondrules, yielded by shock waves around planetesimals in the protoplanetary disk, have relative velocities of 2–4 m s^{-1} to the gas flow (Yasuda et al., 2009). In the case of dust accretion on a chondrule, relative velocity between dust and a chondrule should have been less than 1 m s^{-1} (Kring, 1988).

Millimeter-sized aggregates have potentially some hurdles to overcome before they can grow further, due to the onset of fragmentation (Blum and Wurm, 2008), fast radial drift (Weidenschilling, 1980), and bouncing in mutual collisions (Güttler et al., 2010; Zsom et al., 2010). The latter is, however, possibly not a show-stopper for the further growth, as Windmark et al. (2012a,b) and Garaud et al. (2013) have recently shown. Velocity variations (Garaud et al., 2013) or the introduction of centimeter-sized or larger particles lead to a growth of dust aggregates well beyond the bouncing barrier.

In this work, we assume that chondrules and matrix were formed at different places in the protoplanetary disk and subsequently collided with each other. We investigated the conditions under which a chondrule is being embedded into the matrix and the penetration depth at a given relative velocity, that is the required minimum initial size for the matrix to capture a chondrule.

2. Experiments

We used polydisperse spherical silica particles (Admafine SO-E3, Admatechs) of 0.8 ± 0.3 μm diameter and 2200 kg m^{-3} mass density as matrix analogs to produce macroscopic dust agglomerates. Electrostatic charges on the agglomerates occur only on the surface layer. The physical impact of electrostatic charging on the collision and impact behavior of the dust aggregates is estimated to be negligible, because the electrostatic forces between the dust grains are much smaller than the adhesion forces of the silica particles (Güttler et al., 2008). For the impact-velocity range from 0.2 to 2 m s^{-1}, we used the 1.5-m drop tube at the University of Braunschweig (Germany) (Beitz et al., 2011). For the velocity range from 2 to 5 m s^{-1}, a spring gun, developed for this study, was used. For the velocity range from 20 to 300 m s^{-1}, a gas-gun installed at Kobe University (Japan) was used (Setoh et al., 2010).

2.1. Impact experiments at low velocities

Dust agglomerates of ~50, ~75, and ~90% porosity were prepared for the collision experiments at the lowest impact velocity. (i) The compacted dust agglomerates of ~50% porosity were prepared by pouring a dust sample into a target container of 3 cm in diameter and 3 cm in height and pressing by hand. (ii) Medium-porosity dust agglomerates of ~75% porosity were prepared by pouring mm-sized dust agglomerates of 68% porosity each into an identical container. The determination of the porosity of the individual mm-sized dust agglomerates was conducted with the same technique as described by Weidling et al. (2012): the small agglomerates were put on a rotating stage and images were taken during a full rotation of 360° around the vertical axis. The diameter of the agglomerate was measured for each horizontal pixel line in the image sequence. The volume of each horizontal slice was calculated by determining the largest and the smallest diameter and assuming an elliptic shape. The volume was then calculated by integrating the volumes of the slices. We used sieves with mesh sizes of 1.0 and 1.6 mm to form these dust agglomerates. (iii) Fluffy target agglomerates of ~90% porosity were prepared using the random ballistic deposition apparatus described by Blum et al. (2006).

The solid projectiles used in our experiments were glass beads of 1 mm (with a mass of 1.6 mg) or 4.7 mm (150 mg) diameter. The experiments were free from gravitational influence by releasing both, the target and the projectile, at slightly different times, using a two-level release mechanism. The release mechanism of the dust target inside the plastic container consisted of a plate, which was mounted to a rotary solenoid of the lower release mechanism. The projectile particle was suspended on a thin string, held in place by a linear solenoid of the upper release mechanism, in the same fashion as described by Beitz et al. (2011). By adjusting the release height of the projectile and the timings for dropping the projectile and the target, the relative impact velocities between the projectiles and the targets were set to 1–2 m s^{-1} and 0.1–0.2 m s^{-1}, respectively. A high-speed camera was synchronously dropped outside the glass tube and observed the impacts at a frame rate of 100 fps using back-light illumination. All experiments were performed under vacuum conditions with typical gas pressures of 100 Pa. The experimental conditions are shown in Table 1.

2.2. Impact experiments at medium velocities

Target agglomerates of about 3 cm in diameter, about 7.5 cm in height and 75% in porosity were prepared for the collision experiments at medium velocities (~3 m s^{-1}), using a spring gun. A toy sling was used at ~1.5 m s^{-1}. Sifted dust powder was poured into a container of 3 cm in diameter and ~10 cm in height. A stainless steel rod of a mass of 450 g was then put on the top of the sample to compress the powder to a porosity of about 75%. The axis of the cylindrical container was then turned to horizontal.

The projectile trajectories were horizontal and normal to the surface of the target. A glass bead of ~3 mm in diameter (~30 mg in mass) as a projectile was put into a small cylindrical hole at the top of the spring gun. By adjusting the length of the spring before the shot, the impact velocity could be adjusted between ~2 m s^{-1} and ~5 m s^{-1}. The impact was observed by a high-speed camera (Photoron FASTCAM SA1.1) which was operated at 10 kfps. All experiments were performed under atmospheric pressure. Because the compressive strength of targets of