Icarus 241 (2014) 1–12

Contents lists available at ScienceDirect

Icarus

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

Laboratory experiments on the impact disruption of iron meteorites at temperature of near-Earth space

Takekuni Katsura [a], Akiko M. Nakamura [a,*], Ayana Takabe [a], Takaya Okamoto [a], Kazuyoshi Sangen [a], Sunao Hasegawa [b], Xun Liu [c], Tsutomu Mashimo [c]

[a] Department of Earth and Planetary Sciences, Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan
[b] Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara-city, Kanagawa 252-5210, Japan
[c] Institute of Pulsed Power Science, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555, Japan

ARTICLE INFO

Article history:
Received 22 October 2013
Revised 5 June 2014
Accepted 10 June 2014
Available online 20 June 2014

Keywords:
Impact processes
Collisional physics
Asteroids
Meteorites

ABSTRACT

Iron meteorites and some M-class asteroids are generally understood to be fragments that were originally part of cores of differentiated planetesimals or part of local melt pools on primitive bodies. The parent bodies of iron meteorites may have formed in the terrestrial planet region, from which they were then scattered into the main belt (Bottke, W.F., Nesvorný, D., Grimm, R.E., Morbidelli, A., O'Brien, D.P. [2006]. Nature 439, 821–824). Therefore, a wide range of collisional events at different mass scales, temperatures, and impact velocities would have occurred between the time when the iron was segregated and the impact that eventually exposed the iron meteorites to interplanetary space. In this study, we performed impact disruption experiments of iron meteorite specimens as projectiles or targets at room temperature to increase understanding of the disruption process of iron bodies in near-Earth space. Our iron specimens (as projectiles or targets) were almost all smaller in size than their counterparts (as targets or projectiles, respectively). Experiments of impacts of steel specimens were also conducted for comparison.

The fragment mass distribution of the iron material was different from that of rocks. In the iron fragmentation, a higher percentage of the mass was concentrated in larger fragments, probably due to the ductile nature of the material at room temperature. The largest fragment mass fraction f was dependent not only on the energy density but also on the size d of the specimen. We assumed a power-law dependence of the largest fragment mass fraction to initial peak pressure P_0 normalized by a dynamic strength, Y, which was defined to be dependent on the size of the iron material. A least squares fit to the data of iron meteorite specimens resulted in the following relationship: $f \propto \left(\frac{P_0}{Y}\right)^{-2.1\pm0.2} \propto d^{-0.87\pm0.15}$, indicating a large size dependence of f. Additionally, the deformation of the iron materials in high-velocity shots was found to be most significant when the initial pressure greatly exceeded the dynamic strength of the material.

1. Introduction

Over 1000 iron meteorites have been collected on Earth (Meteoritical Bulletin Database). The parent bodies of the majority of iron meteorites, which lack significant amounts of silicates, are generally understood to have been originally the cores of differentiated bodies ("magmatic" or "fractionally crystallized groups" meteorites). Other meteorites, such as those from the "non-magmatic" "silicate-bearing groups," experienced a crystallization history and environment substantially different from the simple fractional crystallization of an undisturbed metallic melt (Goldstein et al., 2009). According to ^{182}Hf–^{182}W chronometry, magmatic iron meteorites were segregated a few million years after CAI formation (Qin et al., 2008) and W and Sm isotope measurements of specimens from non-magmatic iron meteorites show that melt pool formation events occurred over a time-span of 28 Ma which can only be explained via external heat sources, e.g., impact events (Schultz et al., 2012). Based also on cosmic-ray exposure ages, iron meteorites reached their present size by collisional disruption within 1.5 byr from the present (Eugster et al., 2006).

Bottke et al. (2006) proposed a scenario in which iron meteorite parent bodies formed in the terrestrial planet region, after which they were scattered into the main belt by collisions, Yarkovsky thermal forces, and resonances. Some of M-class asteroids in the

* Corresponding author. Fax: +81 78 803 5791.
E-mail address: amnakamu@kobe-u.ac.jp (A.M. Nakamura).

http://dx.doi.org/10.1016/j.icarus.2014.06.007
0019-1035/

main belt, such as 16 Psyche and 216 Kleopatra, are considered to have a metallic component based on their high radar albedos (Shepard et al., 2008). However, the lower bulk densities of these bodies, 4.02 ± 1.36 g cm^{-3} and 3.6 ± 0.4 g cm^{-3} (Baer and Chesley, 2008; Descamps et al., 2011), respectively, compared with iron meteorite material show that they are not homogenous bodies of iron meteorite composition. Spectroscopic observations of most of the highest metal-content asteroids, as suggested by radar, tend to exhibit silicate absorption features at both 0.9 and 1.9 μm (Ockert-Bell et al., 2010).

Between the segregation of the iron and the last collision event that exposed the iron meteorites in interplanetary space, the parent bodies and fragments must have experienced collisional events over a range of mass scales and impact velocities at different temperature. Metallic bodies would also have acted as effective impactors to shatter or disperse rocky bodies owing to their high density and mechanical impedance. A microscopic and X-ray diffraction study suggested that approximately 50% of all iron meteorites reaching the Earth have been pre-terrestrially shocked to pressures in excess of 13 GPa (Jaeger and Lipschutz, 1967).

Iron materials have a brittle–ductile transition at a certain temperature. The transition temperature depends on metallurgical factors such as grain size and purity, and on conditions such as strain-rate and confining pressure (Johnson and Remo, 1974). A low strain rate tensile experiment of the Gibeon iron meteorite (VIA, one of magmatic group) showed the ductility fell off with a decrease in temperature, but not as suddenly as in iron with a body-centered cubic (BCC) crystal structure, and significant ductility is retained down to 103 K (Gordon, 1970). Charpy V-notch impact specimens prepared from Henbury (IIIAB) and Hoba (VIB) magmatic iron meteorites showed that Henbury was almost totally brittle but Hoba was fully ductile at 195 K (Remo and Johnson, 1975; Johnson et al., 1979). Matsui and Schultz (1984) performed impact experiments on iron meteorite targets Gibeon, El Sampal (IIIAB), and Arispe (IC) at 290 K and at low temperature (<200 K). The targets were 6000 times heavier than their projectiles, so the targets were not disrupted. Impacts with velocity of 5 km s^{-1} resulted in a net mass loss of the targets regardless of the brittle–ductile behavior of the target or projectile, whereas impacts at 2 km s^{-1} resulted in a net mass gain, i.e., the projectiles were accreted onto the targets, for ductile projectiles into brittle and ductile targets.

The impact outcome is characterized by the threshold energy density, the specific energy to shatter Q^*_S and the specific energy to disperse Q^*_D. The specific energy to shatter Q^*_S is defined as the ratio of projectile kinetic energy to the target mass (or the sum of the target and projectile masses) required to produce the largest intact fragment that contains one-half the target mass, and Q^*_D is defined as the ratio of projectile kinetic energy to the target mass so that the largest object following re-accumulation is one-half the mass of the original body (Holsapple et al., 2002). The data on impact disruption of iron meteorite are sparse despite the large variety of iron meteorites and their temperature dependence. Impact disruption experiments for cooled Gibeon targets were conducted and the Q^*_S value was determined to be much larger than that of rocks and ices (E. Ryan, private communication; Ryan et al., 1999; Holsapple et al., 2002). The mass fractions of iron-meteorite (Campo del Cielo) projectile relics recovered in two hypervelocity cratering experiments with dry sandstone targets performed at room temperature were shown in a previous study (Kenkmann et al., 2013).

In this study, we conducted impact experiments on iron meteorites at room temperature to increase understanding of the collisional outcomes of iron bodies, which can be applied to the study of the collisional evolution of small bodies, i.e., the size distribution of small bodies, in near-Earth space. If the iron-meteorite parent bodies formed in the terrestrial planet region (Bottke et al., 2006), the collisions that they experienced before being scattered into the main belt may have affected the size distribution of the iron bodies in the main belt. The size distribution of the iron bodies could also have played a key role in chemical processes in the early Solar System, e.g., in the formation of Earth's core (Karato and Murthy, 1997).

2. Experiments

We performed impact experiments using four different guns to examine a wide range of parameters. Impact experiments with velocities of 1.3–5.1 km s^{-1} were performed using 7-mm bore two-stage helium gas and hydrogen gas guns at the Institute of Space and Astronautical Science (ISAS). Although the expected typical impact velocity is higher than that achieved in this study, from 8 to 12 km s^{-1} for those with a semi-major axis of 0.5–2 AU (Bottke et al., 2006), the velocity range of this study corresponded to the low-velocity tail of the velocity distribution. It may also correspond to the effective impact velocity of oblique incidences. The most likely angle of impact is 45°, and half of the events occur at an angle of less than 45°, i.e., at a more oblique incidence angle (Gault and Wedekind, 1978, and references therein). Previous laboratory impact experiments using basalt targets showed that the largest fragment mass fraction at an incidence angle between 40° and 50° corresponds to that at a normal incidence angle with an energy density of about half or slightly less (Fujiwara and Tsukamoto, 1980; Nakamura, 1993). These results indicated that the effective impact velocity at an incidence angle of 45° or shallower is roughly less than 0.7 times the normal impact.

In order to simulate collision between iron and rocky bodies, we launched iron-meteorite projectiles up to 4 mm in diameter into larger rocky targets. Additional shots with iron-meteorite targets of 5.4 mm in diameter were conducted using nylon projectiles. Experiments with larger iron-meteorite projectiles with diameter of 7.5 mm and targets 20 mm on a side and 36 mm in diameter were performed using a 20-mm bore two-stage helium-gas gun at Kumamoto University, which was transferred from Tohoku University to Kumamoto University (Syono and Goto, 1980). Although we focus on the outcome of collisional disruption of iron, the outcome of collisional disruption of the rocky targets by iron projectiles are briefly addressed in this study, therefore, results of impact experiments of nylon projectiles and the rocky targets of the materials used in the iron-meteorite shots are shown for comparison.

Another series of impact experiments of iron-meteorite targets with diameter of 5.4–15 mm were conducted using a 15-mm bore vertical powder gun at Kobe University (Nagaoka et al., 2014 and references therein) with velocities up to 0.94 km s^{-1}. Metals and plastics are usually used with this gun, therefore, we chose metal projectiles to attain larger initial pressure than those attained by rock or plastic projectiles with the same impact velocity.

Disruption experiments with steel projectiles or targets were also conducted in order to increase the data of iron materials for better understanding of the outcome of iron-meteorite impacts.

In the following, we describe the experimental setups of those conducted using the two-stage light-gas guns and those conducted using the powder gun, separately.

2.1. Two-stage light-gas guns experiments

Projectiles were accelerated to the vacuum chamber horizontally. The projectile velocity was determined from the time intervals between the arrival of the projectile at two and three laser beams for the helium and hydrogen guns, respectively at ISAS. A