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On the Brittle-Ductile Behavior of Iron Meteorites: New Experimental Constraints

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High-velocity (~2 to ~5 km/sec) impacts into octahedrite iron meteorites (Gibeon, El Sampal, and Arispe), steel, and iron targets were made at the NASA-Ames Vertical Gun Facility. The experiments clearly revealed the brittle behavior of meteorites at very low temperatures (<200° K) as indicated by spallation of the crater rim and the development of deeply penetrating fractures in the meteorite sample. Although failure also occurred at higher temperatures (290° K), it was restricted to near-surface spalls. High-velocity (~5 km/sec) impacts resulted in a net mass loss regardless of the brittle-ductile behavior of the target or projectile, whereas low-velocity (~2 km/sec) impacts resulted in a net mass gain for ductile projectiles into brittle and ductile targets. Consequently, even if iron meteorites (octahedrites) were originally the core of a layered parent body, they might be subsequently destroyed in a brittle manner. Such results are consistent with the hypothesis by Matsui and Mizutani (1977) that the brittle behavior of iron-like planetesimals in the low-temperature asteroid zone prevents growth into full-size planets.

INTRODUCTION

Theories concerning the formation and evolution of asteroids can be broadly classified into two scenarios. The first describes asteroids and planets initially accumulating both the silicate and metal fractions simultaneously; these are homogeneous-accretion models. Through heating and differentiation, a metallic core is formed with a silicate mantle [e.g., see reviews by *Chapman*, 1979, and *Wilkening*, 1979]. The second scenario describes assemblage of the metal core of asteroids and planets before acquisition of the silicate mantle. *Orowan* [1969] provided an early conceptual basis for such a heterogeneous-accretion model on which a more physical and quantitative basis has been provided by *Matsui and Mizutani* [1977]. The present paper provides additional support for the heterogeneous-accretion model through laboratory experimentation.

The mechanical properties of planetesimals have been suggested to play an important role in determining whether or not growth of planetesimals occurs [*Matsui and Mizutani*, 1977; *Matsui*, 1979; *Matsui et al.*, 1982]. Collisional coagulation of rocky materials at temperatures much below the melting temperature is supressed by the brittle behavior of rocky materials. Even if gravitational coagulation (accretion of fragments due to gravitational capture of the largest fragment) is considered, rapid growth of rocky planetesimals by accretion cannot be expected to proceed in the early stage of planetary formation owing to the low escape velocities [*Matsui and Mizutani*, 1977]. The collision process of planetesimals thus may be viewed as competition between coagulation and fragmentation. If the existence of the asteroid belt in the present solar system reflects the fragmentation-dominant case, then some retarding condition for planetesimal growth by accretion prevailed in this region in the past. In contrast, the four terrestrial planets and the earth's moon in the inner solar system demonstrate that conditions suitable for the growth of planetesimals prevailed. What are the major differences between these two regions? *Matsui and Mizutani* [1977] suggested that some nucleating agent is required for the rapid formation of the terrestrial planets and proposed the ductile property of iron meteorites as a possible agent. Ductile materials can absorb the impact energy by plastic deformation (up to a limit); consequently, coagulation of ductile materials after collision is expected to occur much more efficiently than coagulation of brittle materials. If this reasoning is correct, then the major question is why the minor planets (asteroids) are minor. The reason is possibly due to a change in mechanical properties of iron-meteorite-like planetesimals. To test this hypothesis, we performed a series of exploratory experiments at the NASA-Ames Vertical Gun Range.

BACKGROUND

In the asteroid region of the solar system, even iron-meteorite-like planetesimals cannot behave in a ductile manner because of the low temperatures (<200° K). The existence of a brittle-ductile transition at low temperatures has been previously demonstrated for iron alloys having a body-centered cubic structure [*Johnson*, 1962]. Kamacite is a dominant phase in iron meteorites. Since kamacite is a nickel-iron alloy with body-centered cubic structure, we can expect the existence of a brittle-ductile transition for iron meteorites. Most iron meteorites show a texture consistent with brittle failure [*Gordon*, 1970]. At static or low strain rate conditions, a brittle-ductile transition at very low temperature (50° K) exists [*Auten*, 1973]. Since the temperature for brittle-ductile transition (T_{BD}) is also dependent on strain rate [*Johnson and Remo*, 1974], pendulum hammer experiments were performed by *Remo and Johnson* [1975] for the Henbury iron meteorite between 195° and 300° K. At 195° K, the Charpy specimen (a sample of standardized

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TABLE 1. Experimental Results from Impacts into Meteorites and Steel

No.	Projectile type (cm)	Projectile m(g)	Target type	Target M(g)	T(°K)	v(km/s)	ΔM/m[**]	Comments
830301	0.476 steel[*]	0.4396	Gibeon	773.7	213	5.5	-	meteorite fractured
830304	0.318 steel[†]	0.1423	Gibeon	812.2	294	(5)[§]	-	failure (spalls) near surface along Widmanstatten pattern
830305	0.318 steel[†]	0.1423	steel[‡]	1133.29	294	4.95	−6.39	no fractures
830306	0.318 steel[†]	0.1423	Gibeon	583.82	107	(5)	−2.60	deep fracture; no surface spalls; square crater
830307	0.476 basalt	0.1569	Gibeon	633.43	104	(5)	−2.55	failure (spalls) along Widmanstatten pattern
830309	0.318 steel[†]	0.1423	Arispe	50.01	294	(1.9)	+ 0.70	failure (spalls) along Widmanstatten pattern
830606	0.318 steel[†]	0.1423	steel[‡]	49.2913	296	1.88	+ 0.84	no fractures
830607	0.318 steel[†]	0.1420	El Sampal	52.5870	93	(1.9)	+ 0.54	fractures and spalls
840301	steel[†]	0.1416	iron	252.40	293	5.03	−3.53	no fracture
840302	steel[†]	0.1416	iron	252.20	103	5.00	−2.12	fracture
840303	steel[†]	0.1416	iron+sand	252.35	143	4.92	+ 0.353	no fracture
840304	steel[†]	0.1416	iron+sand	251.40	289	5.26	0	no fracture
840305	steel[†]	0.1416	Toluca[‖]	355.45	143	5.26	−32.1	failure along Widmanstatten pattern
840306	steel[†]	0.1416	iron	251.40	113	4.14	−1.77	fracture
840307	steel[†]	0.1416	Toluca[‖]	323.95	291	5.17	−16.6	deep fracture; surface spalls
840308	steel[†]	0.1416	iron	251.45	292	3.88	−0.353	no fracture
840309	steel[†]	0.1416	iron	251.30	113	1.74	−0.706	off center; fracture at edge
840310	steel[†]	0.1416	iron	251.45	118	1.63	0	off center; fracture at edge
840311	steel[†]	0.1416	Toluca[‖]	185.15	115	3.38	−23.3	fracture along Widmanstatten pattern
840312	steel[†]	0.1416	iron	251.55	270	2.22	+ 0.706	no fracture
840313	steel[†]	0.1416	Toluca[‖]	223.20	285	2.36	−2.12	fracture along Widmanstatten pattern
840314	steel[†]	0.1416	iron	251.50	290	2.36	+ 1.06	no fracture

*High-carbon steel.
†High stainless steel.
‡No. 1020 steel (0.18–0.23% carbon; 0.3–0.6% manganese; 0.04% maximum phosphorus; 0.05% maximum sulfur).
§Velocities in parentheses are estimates based on equivalent launch parameters.
‖Meteorites had three surfaces covered by oxide shales that spalled during impact.
**ΔM/m indicates the mass gained (+) or lost (–) relative to the projectile mass.

geometry and size) absorbed only 6.9×10^4 ergs of energy during fracture, whereas at 300° K, 2.8×10^5 ergs were absorbed. Based on such comparisons of absorbed energy during fracture, they concluded that T_{BD} is in the vicinity of 200° K. However, if T_{BD} is a function of strain rate, their experimental conditions remain unsatisfactory for studying the conditions required for the impact-induced brittle fracture of the iron meteorite parent bodies or the iron-meteorite-like planetesimals in the asteroid region of the solar system. Because the present impact velocity in the asteroid belt is considered to be about 5 km/s, high-velocity impacts on iron meteorites were performed with the NASA-Ames Vertical Gun Range Facility. The experimental results reported here are exploratory to date but provide new constraints concerning collisional destruction of iron meteorites.

EXPERIMENTAL PROCEDURE

Meteoritic, steel, and iron targets were impacted at temperatures ranging from about 100° K to 300° K with velocities from 1.6 km/s to 5.5 km/s. Target samples were cooled by conduction as liquid nitrogen passed through an aluminum target holder. Samples were held in close contact with the holder by brass shims on three sides. A thermocouple inserted about 1 cm in a small hole at one corner of the target permitted monitoring the temperature. Although not measured, the temperature gradient in the target is believed to have been small due to the conductivity of the sample and the long cooling times (two hours). Table 1 summarizes the experimental conditions. All impacts occurred under low atmospheric pressures (<1.0 mb). Although impact velocities did not register in a few experiments, we have estimated the velocity based on successful records with the same launch conditions. The high-velocity impacts (~5 km/sec) used a two-stage light-gas gun, whereas the low-velocity impacts (~2 km/sec) used a single-stage powder gun. The former experimental series involved large target-to-projectile mass ratios (1800–8000) with sample sizes approximately $4 \times 4 \times 3$ cm (Gibeon meteorite and steel). Although the typical impact energies were high (2×10^{10} ergs), they were insufficient to destroy the target. The powder-gun series used smaller target-to-projectile ratios (~360) with sample sizes about $3 \times 3 \times 0.7$ cm (Arispe and El Sampal meteorites and steel). In this series, nearly complete rupture occurred.

At room temperature, impacts into steel and iron targets produced the classic ductile behavior including the following features: hemispherically shaped crater; upturned and overturned rim flap; and projectile plating the crater cavity [see *Summers*, 1959]. No failure was observed in the steel or iron targets impacted at high or low velocity; hypervelocity impacts into meteorites at room temperature exhibited slightly different behavior (Figure 1*a*). The crater shape, crater lip, and projectile-plated cavity resembled craters in steel. However, cross-hatched ridge patterns developed within a crater diameter of the rim and reflected the characteristic Widmanstätten pattern. The surface relief associated with this pattern most likely reflects the contrasting impedance between kamacite and taenite. In addition, minor fracturing occurred but was typically associated with spalls at sharp free-surface boundaries (see Figure 1*a*). Cross-sectioned inclusions exposed at the surface typically popped out during impact.

At impact velocities lower than 2 km/s (No. 830309, cf. Table 1), the same phenomena occurred (Figure 2*a*). Even at room temperature the large dynamic stresses resulted in failure, but the fractures characteristically appeared to follow the Widmanstätten pattern. As noted above, such failure may be related to the small sample size. The cross-hatched ridge pattern reflecting the mismatched impedance between the kamacite and taenite did not develop.

At low temperatures (213° K), the hemispherical crater cavity was unchanged, but the crater rim showed significant differences (Figure 1*b*). The crater rim became irregular with craggy elements. Pieces of the rim were spalled, typically where the Widmanstätten pattern intersected the rim. A deep fracture penetrating the sample contrasted with the surface spalls produced by impacts at room temperatures. At very low temperatures (107° K), the craggy appearance was more pronounced as near-rim spallation became important, a characteristic of brittle failure. The crater shape became polygonal with parallel sides conjugate to the meteorite fabric. More significantly, a deep body fracture developed halfway through the sample. Such a fracture probably reflects the interaction of reflected tensile waves that are less damped in the cold target, thereby exceeding the dynamic tensile strength of the sample. This fracture showed no obvious control by the Widmanstätten pattern.

The low-velocity impact at very low temperatures (No. 830607, see Table 1) also clearly showed the brittle behavior of the meteorite (Figure 2*b*). The rim was irregular and large spall zones developed, in contrast with the impact at room temperatures (No. 830309) as shown in Figure 2*a*. Break-up of the meteorite sample occurred at both 294° K and 93° K, very likely because the samples were relatively thin; in fact, the projectiles penetrated nearly halfway through the sample. At room temperatures this deep penetration resulted in a bulge on the backside. At very low temperatures irregular spall fractures occurred, and the steel projectile nearly recoiled out of the crater cavity. More detailed comparisons cannot be made at this time owing to the off-center impact of No. 830309.

An additional exploratory impact experiment (No. 830308) used a high-velocity basalt sphere to examine the possible conditions that produce mesosiderite-like structures. The mesosiderite is a stony-iron meteorite that has been classified as a breccia in which angular silicate fragments are distributed in a matrix of disseminated fine metals. The experiment was performed to see if the basaltic fragments could penetrate into the iron meteorite. During launch, the weaker basaltic projectile fragmented; nevertheless, the resulting craters were plated with the comminuted basaltic material. For large target-to-projectile mass ratio (>4000), brittle failure beneath the crater did not appear to occur. Consequently if basalt-iron collisions are responsible for the mesosiderites, then we suspect that complete brittle fragmentation of the iron meteorite is necessary. Such a process might occur for larger impacts where shock-spalled and fractured zones are injected with the comminuted basalt impactor.

In most of the experiments we tabulated the mass loss or mass gain resulting from the impacts. All high-velocity impacts resulted in a net mass loss (about 2.5 projectile masses) owing to the hydrodynamic behavior of the event and partial ejection of the melted target/projectile (see Figure 3). The only exceptions were impacts into iron targets covered with a thin veneer (0.1 cm) of sand. In these experiments, the sand veneer suppressed fracturing and mass loss from the solid sample. All low-velocity impacts resulted in a net mass gain (less than one projectile mass) since the projectile remained trapped in the impact cavity. This may be an anomalous result, however, because we primar-

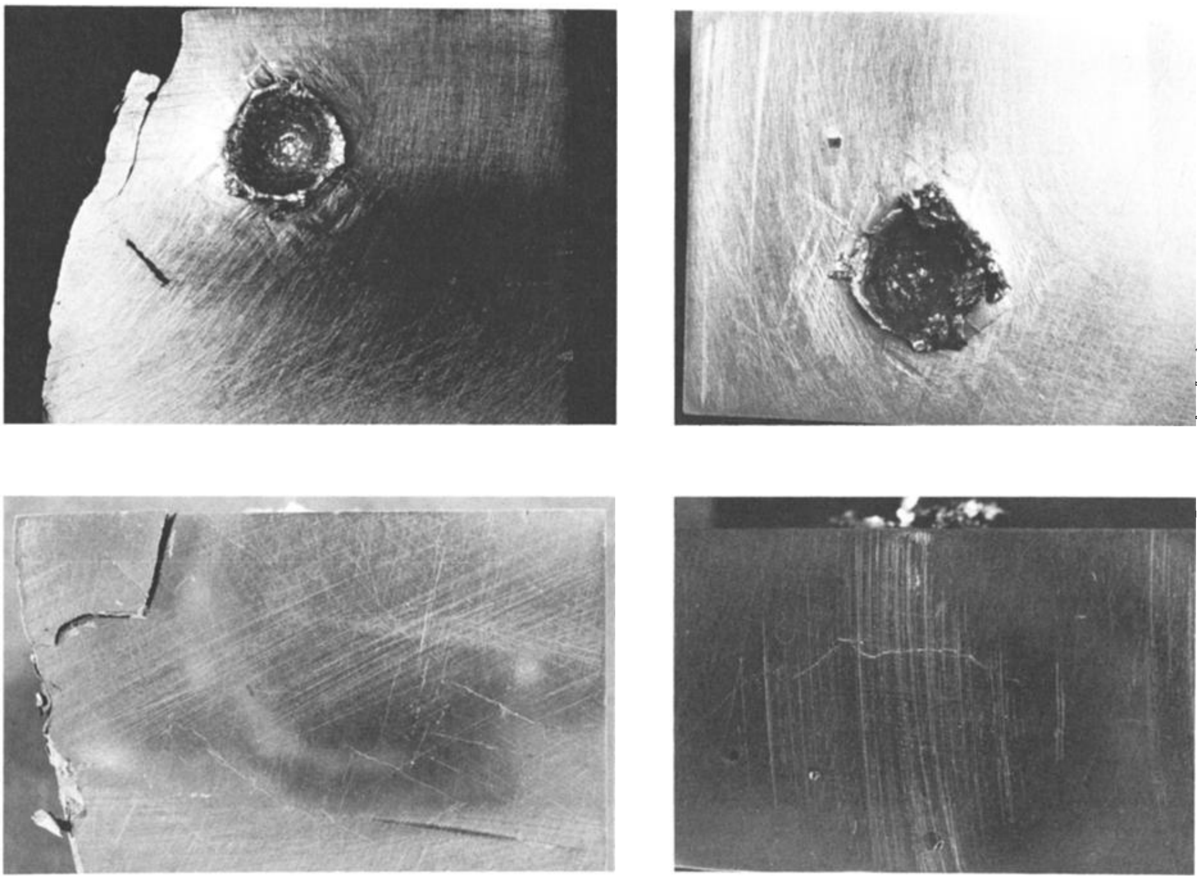

Fig. 1*a* Fig. 1*b*

Fig. 1. High-velocity impacts at about 5 km/s by 0.318 cm steel balls into samples of the Gibson meteorite at room (294° K) and reduced (107° K) temperatures (Figures 1*a* and 1*b*, respectively). At room temperatures, the crater lip and symmetrical shape (top view) indicate ductile behavior of the target although near-surface cracks and spalls occur along discontinuities of the Widmanstätten pattern. At low temperatures, the craggy crater lip and polygonal shape (top view) suggest brittle failure and a deep fracture splits the sample (bottom).

ily used ductile projectiles in order to achieve successful launches (unbroken projectiles) for these exploratory experiments. On the basis of the one experiment with a brittle basalt sphere as well as experience with impacts into sand, we strongly suspect that future experiments at low temperatures will result in a net mass loss—even at low impact velocities—owing to fragmentation and ejection of the projectile.

CONCLUSIONS

The experiments described above provide the following preliminary conclusions. First, the very low dynamic stresses produced in the experiments by *Remo and Johnson* [1975] may be valid for large distances from the impact point but are clearly inappropriate near the impact. In particular, we observed spallation of the meteorite samples even at room temperature owing to the large dynamic stresses produced. Second, the experiments clearly revealed the brittle behavior of meteorite targets at very low temperatures (<200° K). This behavior was indicated by the occurrence of spallation of the crater rim and the development of deeply penetrating fractures in the meteorite target. Although failure also occurred at higher temperatures (290° K), it was restricted to near-surface spalls and fractures along the Widmanstätten pattern. Third, high-velocity impacts result in a net mass loss regardless of the brittle/ductile behavior of the target or projectile, whereas low-velocity impacts result in a net mass gain for ductile projectiles into brittle and ductile targets. We suspect, however, that brittle projectiles impacting a brittle target will result in a net mass loss as observed at the higher velocities.

The above results demonstrate that octahedrite iron meteorites can suffer brittle fragmentation at low temperatures. Therefore even if iron meteorites were originally located at the central part of the parent body, possibly comprising a core, they might be later destroyed in brittle manner. As pointed out by *Johnson and Remo* [1975], we do not need to consider a so-called "raisin bread" model to explain the interior structure the parent body of the octahedrite iron meteorite [*Auten*, 1973]. However, we may be forced to consider a raisin-bread-like model for the parent body of the ataxite iron meteorite since the ataxite contains large amounts of Ni. As mentioned before, the brittle-ductile transition does not exist for the iron alloys with high Ni content even at lower temperatures.

The above results are also consistent with the idea proposed

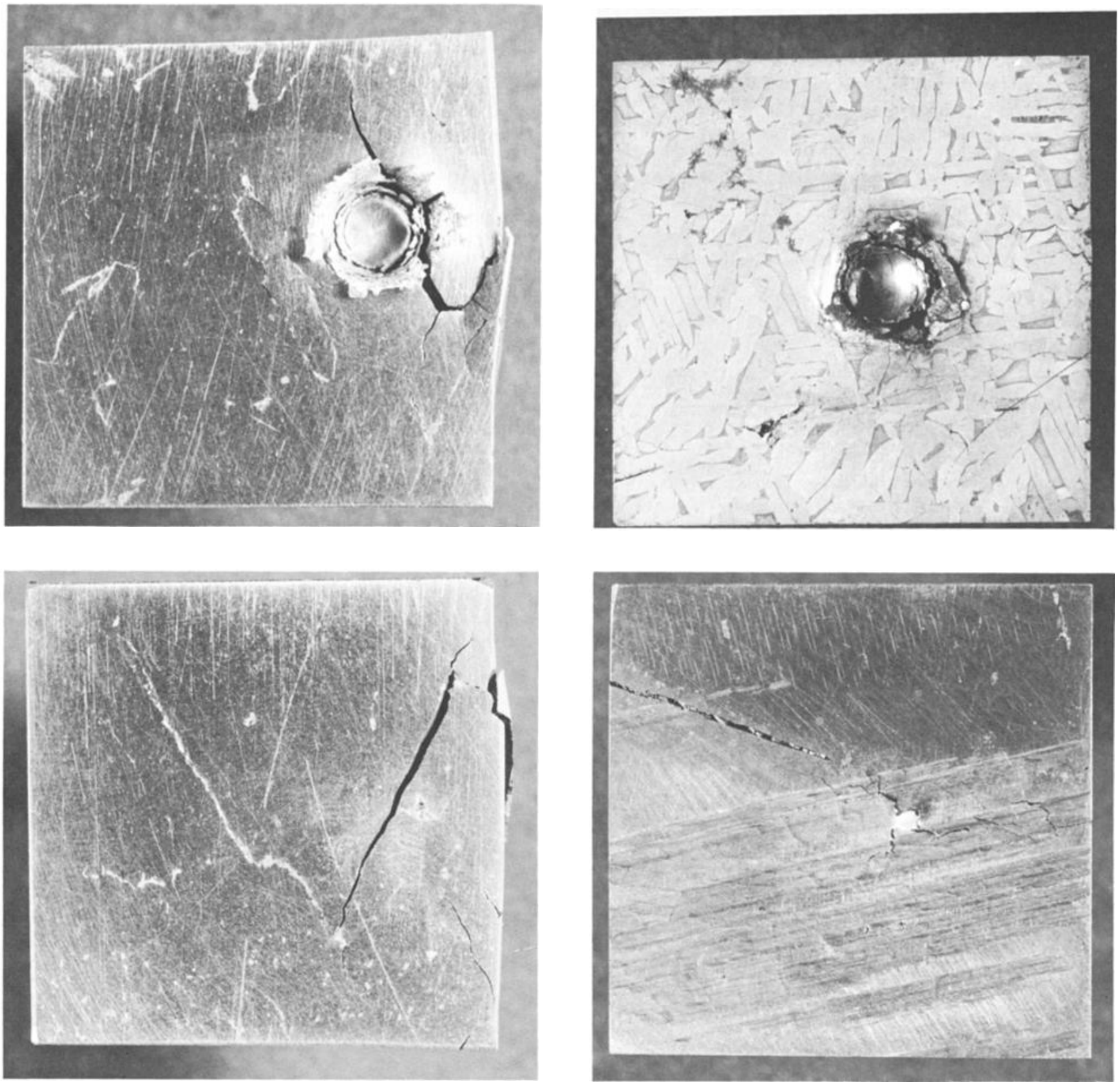

Fig. 2*a* Fig. 2*b*

Fig. 2. Low-velocity impacts at about 1.9 km/sec by 0.318 cm steel balls into Arispe and El Sampal samples at room (294° K) and cooled (93° K) temperatures (Figures 2*a* and 2*b*, respectively). At room temperatures, the peeled-back crater rim and embedded projectile indicate ductile behavior (top view). Nevertheless, the small sample nearly shattered (backside view, bottom). Brittle behavior is observed around crater at low temperatures with spalled crater rim and recoiled projectile (top view). Backside spallation and cracks cut sample (bottom view).

by *Matsui and Mizutani* [1977] on why the minor planets (asteroids) are "minor." In the *Matsui and Mizutani* model, iron-meteorite-like materials could coagulate selectively and thus form the nucleus of a protoplanet in the inner region of the solar system at the beginning of planetary formation. In the low temperatures in the asteroid-belt region, however, iron-meteorite-like materials cannot coagulate during collision. The experiments suggest that coagulation requires the ductile behavior of the projectile and velocities below about 3–4 km/sec. As the mass of the nucleus increases, the escape velocity increases and rocky materials may be retained. Therefore a protoplanet originating from such a heterogeneous accretion should have had a heterogeneous internal constitution; i.e., the innermost part being exclusively composed of iron-nickel alloy with the proportion of the metal decreasing toward the outer part. The innermost part of such a protoplanet may have survived 4.6 b.y. and remains today as a solid inner core for the earth.

Although the experiments do not prove the heterogeneous-accretion model for the origin of present-day asteroids and planetary metallic cores, they at least provide new experimental constraints for a physical mechanism by which such a process could occur. Future experiments are planned that will explore in more detail the mass loss for brittle-brittle collisions and the effects of thin regoliths. In addition, the possibility that basalt-iron collisions could be responsible for the mesosiderites will be examined in more detail.

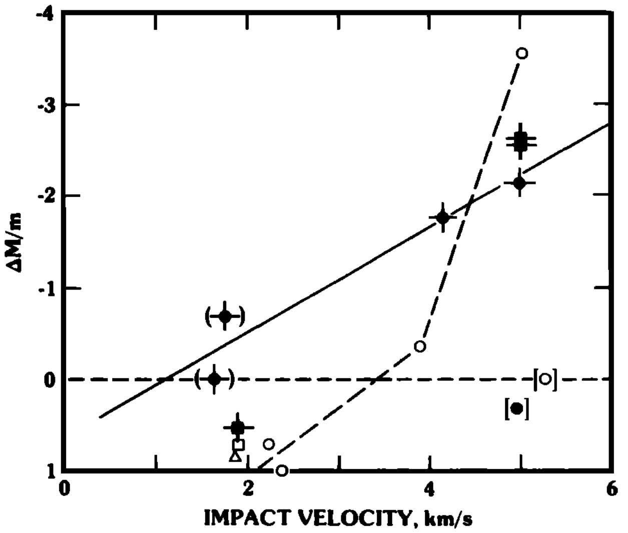

Fig. 3. Mass loss from impacted iron (circles), steel (triangles), and Ni-Fe meteorite (squares) targets at different velocities and temperatures. Open symbols indicate impacts at room temperatures (~295° K), whereas closed symbols indicate cooled samples (~100° K). Impacts at velocities lower than about 3 km/s generally result in a mass gain, whereas higher velocities produce a mass loss. Exceptions include targets where the impact was off center (parentheses) and sand-covered targets (bracketed). Targets that failed in a brittle manner (craggy rim, deep fractures) are indicated by crosses.

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