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Review
Mechanical properties of meteorites and their constituents

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A review is presented of the mechanical properties of meteorites and meteorite constituents. Scientific literature data on the strength of stony and iron meteorites are extremely limited. The average mechanically-measured stony meteorite compressive strength is 200 MPa, while the average iron meteorite compressive strength is 430 MPa. However, the best current estimate of the strength of stony bodies in space may be in the range of only 1–5 MPa, based on observations of meteorite fragmentation due to dynamic atmospheric loading upon Earth entry. Mechanical property and behavior information on both iron-nickel alloy and mineral meteorite constituents is also surprisingly limited in the metallurgical, rock mechanics, and ceramics literature.

1. Introduction
Ever since Comet Shoemaker-Levy 9 struck the Planet Jupiter in 1994, there has been an increasing interest concerning the topic of planetary defense [1, 2]. Mitigation approaches for astronomical bodies that might present a threat to the Earth depend critically on a knowledge of the physical properties of such bodies. However, at the present time, almost nothing is known about the physical properties of asteroids and comets. For example, since the strengths of asteroids or comets have never been directly measured, a major unanswered question is whether they are actually solid objects or are instead “rubble piles” [3]. All of the information presently known about the basic material parameter of asteroid density is summarized in Table I [4, 5].

Meteorites constitute the only materials available on Earth that provide an indication, however approximate, of the physical properties of asteroids. There are three general classes of meteorites: iron, stony-iron, and stony. Iron meteorites (hexahedrites, octahedrites, ataxites) are actually iron-nickel alloys, and are thought to be similar to Type M asteroids. Stony-iron meteorites (pallasites, mesosiderites) are mixtures of iron and stony material, considered related to Type S asteroids. Stony meteorites (chondrites, carbonaceous chondrites, achondrites) constitute the largest number of meteorites that fall to Earth. Chondrites are similar in composition to the Earth’s crust and mantle, and are believed to be associated with smaller Type S asteroids [6]. Carbonaceous chondrites have a composition similar to the Sun (less volatiles), and are thought to be associated with Type C asteroids. A carbonaceous chondrite fragment has recently been discovered in deep-ocean Cretaceous/Tertiery (K/T) boundary sediments [7], and may be a portion of the Chicxulub impactor thought to have destroyed the dinosaurs 65 million years ago. Achondrites are similar to terrestrial basalts, and are believed to have originated on the Moon or Mars.

While the chemistry and mineralogy of meteorites have been studied extensively [8, 9], very little is known about the strength and mechanical properties of these extraterrestrial materials. The purpose of this review is to summarize and discuss what is known about the mechanical behavior of meteorites and meteorite constituents.

2. Mechanical properties of meteorites
There are remarkably few scientific literature references which describe the mechanical properties and behavior of meteorites [10–17]. This is presumably due to the fact that there has not been a strong motivation for obtaining such data until now. Additionally, meteorites

TABLE I Summary of the presently known asteroid densities

Asteroid	Diameter (km)	Bulk Density (g/cm^3)
1 Ceres	974	2.3 (1.98)*
2 Pallas	538	2.6–3.4 (4.2)*
4 Vesta	526	3.3–3.9 (3.9)*
243 Ida	58 × 23	2.6
433 Eros	33 × 13 × 13	2.7**
253 Mathilde	50 × 53 × 57	1.3

*New density data, January 1998, J. L. Hilton, U.S. Naval Observatory.
**New density data, February 1999, Johns Hopkins Univ., Applied Physics Lab.

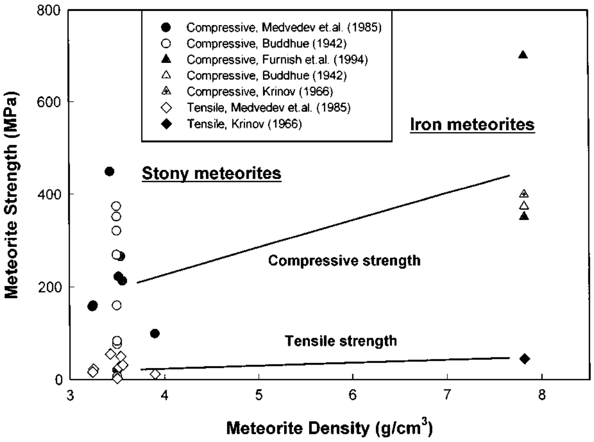


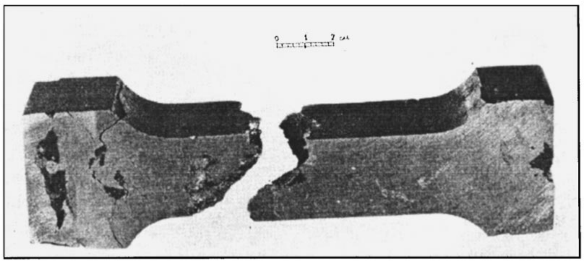
Figure 1 Summary of all data on measured strengths of meteorites existing in the scientific literature.

are relatively rare and thus there is an associated reluctance to use them for mechanical tests.

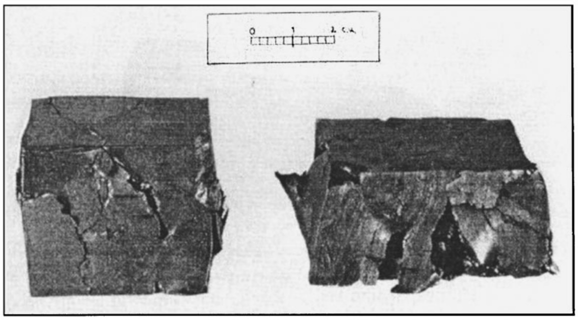
The sum total of all meteorite strength data that exists in the scientific literature is presented in Fig. 1. Most is compressive data, with only a few tensile data points reported. Generally speaking, the reported strength of stony meteorites is lower than that of iron meteorites, although a great deal of scatter exists for both meteorite types. There is no data on the strength of stony-iron meteorites. The average stony meteorite compressive strength is 200 MPa, while the average iron meteorite compressive strength is 430 MPa. For comparison to Fig. 1, terrestrial basalt has a compressive strength of approximately 100 MPa, while iron-nickel alloys containing 7.5 wt.% nickel have a tensile strength of approximately 450 MPa. Meteorite tensile strengths are roughly one order of magnitude lower than compressive strengths, which is typical of relatively brittle materials.

Whether a meteorite material exhibits brittle or ductile behavior depends primarily on its type (i.e. its chemical composition and phase makeup). Stony meteorites are composed of minerals and are essentially brittle materials. Iron meteorites are made up of iron-nickel metallurgical phases (Widmanstatten structures). The Henbury and Hoba iron meteorites exhibited some compressive ductility at room temperature and slow strain rates [15]. However, the Sikhote-Aline iron meteorite showed semi-brittle behavior under these conditions [11], as shown in Fig. 2. For iron meteorites, a ductile-to-brittle transition occurs with decreasing temperature. The Henbury and Hoba meteorites have reported ductile-to-brittle transition temperatures of 200 °K and 145 °K, respectively [12, 13]. For comparison, the average ambient asteroid temperature is approximately 150 °K [18].

The measured strengths of meteorites clearly constitute an upper bound to the actual strengths of asteroids, since meteorites that have been mechanically tested have survived both Earth entry and impact. There is one study in the literature, however, that has estimated the strength of meteorites from observations of their fragmentation due to dynamic atmospheric loading during Earth entry [19]. In this study, the strengths of stony meteorites (densities 2.0–3.7 g/cm^3) were estimated to be in the range of 1–5 MPa. These values are roughly one order of magnitude lower than reported tensile strengths of stony meteorites [14], and may constitute the most realistic estimate available at present for the strength of actual stony asteroids.



Tension - 43 MPa tensile strength



Compression – 398 MPa compressive strength

Figure 2 Mechanical tests on the Sikhote-Aline iron meteorite [11].

3. Mechanical properties of meteorite constituents

3.1. Iron-nickel alloys

Iron meteorites are classified primarily according to the nickel content in iron-nickel alloys [18]. Hexahedrites contain less than 6 wt.% Ni and are composed of the body-centered-cubic (bcc) kamacite phase, with no face-centered-cubic (fcc) taenite phase present. Octahedrites contain 6–16 wt.% Ni and are a mixture of kamacite and taenite phases. Ataxites contain 16–35 wt.% Ni and are composed of taenite with trace amounts of kamacite. The mean chemical composition of iron meteorites contains 9.1 wt.% Ni, with trace amounts of S, C, Co, and P [20]. The Widmanstatten kamacite-taenite phase morphology, which results from extremely slow cooling rates, is the very distinctive metallurgical feature of iron meteorites [21, 22].

Generally and somewhat surprisingly, there is relatively little information in the metallurgical literature on the mechanical properties of iron-nickel alloys. The only data that could be obtained was from relatively old metallurgical references. This is possibly due to the fact that there are few commercial applications for iron-nickel alloys (the only commercial iron-nickel alloy is Invar, which has a composition of 36 wt.% Ni; Invar is a very low thermal expansion alloy). While there is a wealth of metallurgical literature on stainless steels and maraging steels, none of this information is relevant to iron meteorites, since they are iron-nickel alloys with microstructures that have formed as a result of cosmically slow (a few degrees centrigrade per million years) cooling rates.

The room temperature tensile mechanical properties of slowly cooled iron-nickel alloys in the range of 0–40 wt.% Ni are shown in Fig. 3 [23–25]. A maximum in tensile strength occurs in the nickel content range of 10–25 wt.% Ni, while a minimum in tensile ductility is seen in this range. The mean meteorite chemical composition of 9.1 wt.% Ni falls close to the ductility minimum of iron-nickel alloys. Fig. 4 shows the effect of temperature on the mechanical properties of an iron-5 wt.% Ni alloy [23]. The alloy tensile strength increases with decreasing temperature, while the alloy tensile ductility decreases with decreasing temperature. Fig. 5 shows the effect of carbon content on the tensile mechanical properties of an iron-5 wt.% Ni alloy [24]. Strength increases and ductility decreases with increasing carbon content. The average carbon content of iron meteorites is 0.12 wt.% [20].

Another mechanical property of interest is the low temperature, high rate impact behavior of iron-nickel alloys. Limited data exists on iron-nickel alloys. Based on metallurgical Charpy impact tests, the ductile-to-brittle transition temperature of an iron-8.5 wt.% Ni alloy is reported to be in the vicinity of 85 °K [24].

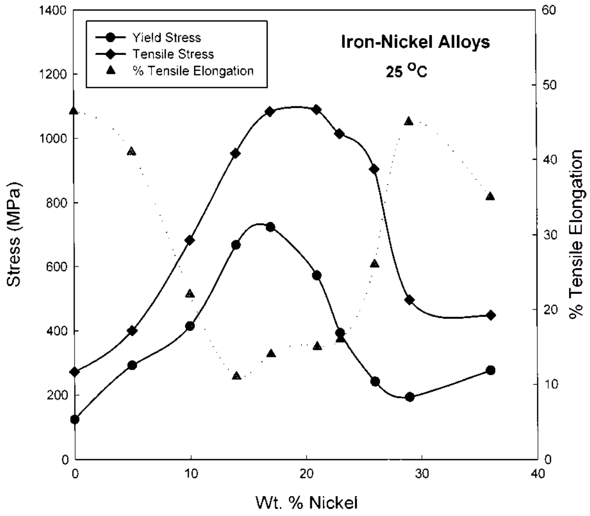


Figure 3 Room temperature tensile mechanical properties of iron-nickel alloys.

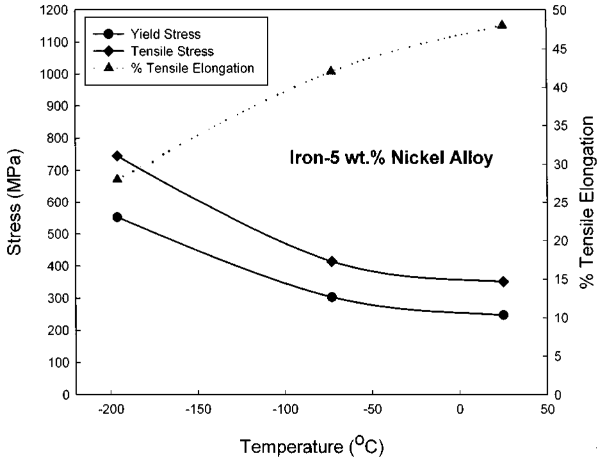


Figure 4 Effect of temperature on the tensile mechanical properties of an iron-5 wt.% nickel alloy.

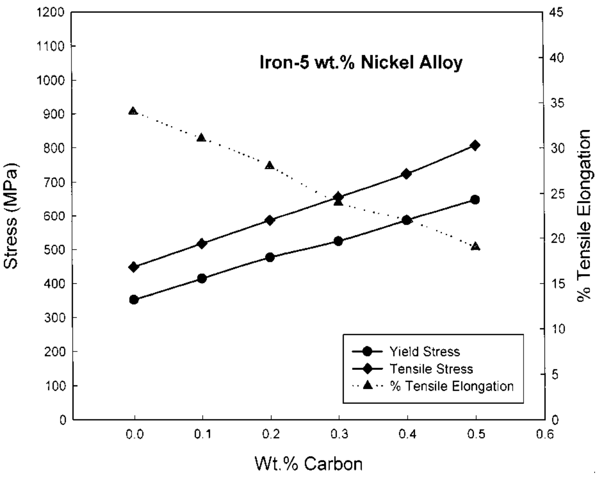


Figure 5 Effect of carbon content on the tensile mechanical properties of an iron-5 wt.% nickel alloy.

3.2. Minerals

The primary mineral species in stony and stony-iron meteorites are the olivine minerals forsterite and fayalite, and the pyroxene minerals enstatite and ferrosilite [20]. These mineral species constitute approximately 75 volume % of chondrite meteorites, and 48 volume % of pallasite meteorites. Shown in Table II are the physical properties of these minerals [20, 26]. Mineral densities range from 3.2–4.4 gm/cm^3, while their melting points range from 1550–1910 °C (a melting point for ferrosilite could not be found in either the ceramic or the rock literature).

The mechanical properties of these minerals have been extensively studied by the rock mechanics community at elevated pressures and temperatures, since they are major constituents of the Earth's crust. However, for the conditions of low temperature and low pressure relevant to asteroids and meteorites, there is almost no data in either the ceramics or the rock mechanics literature. The very limited data that is available are shown in Table III [26, 27, 28, 29]. The reported compressive strength of forsterite is relatively low at 80 MPa. The tensile strength of forsterite is approximately 10% of the compressive strength, which is usually observed for brittle ceramic materials [30].

TABLE II Physical properties of the major meteorite minerals

Mineral	Chemical Formula	Crystal Structure	Density (gm/cm^3)	Melting Point
Forsterite	Mg_2SiO_4	Orthorhombic	3.213	1910 °C
Fayalite	Fe_2SiO_4	Orthorhombic	4.393	1200 °C
Enstatite	$MgSiO_3$	Orthorhombic	3.209	1550 °C
Ferrosilite	$FeSiO_3$	Orthorhombic	3.900	—

TABLE III Mechanical properties of major meteorite minerals at 25 °C and 1 bar

Mineral	Elastic Modulus (GPa)	Shear Modulus (GPa)	Compressive Strength (MPa)	Tensile Strength (MPa)
Forsterite	204	82.2	80	9.5
Fayalite	140	52.9	—	—
Enstatite	180	74.6	—	—
Ferrosilite	—	—	—	—

4. Assessment

From the perspective of planetary defense for potential Earth-threatening asteroids, there is disturbingly little information currently known about the mechanical properties of meteorites, as well as meteorite constituents, that might be employed to estimate the mechanical properties and behavior of asteroids. A key question associated with threat mitigation of an asteroid is whether explosive or impact schemes for asteroid deflection might produce fragmentation, rather than deflection, of the asteroid body. If the asteroid were broken into large fragments on the same trajectory towards Earth, then there would clearly continue to be a significant impact threat. Threat mitigation requires that either suitable asteroid deflection results, or that the asteroid is shattered into small fragments no larger than about ten meters in diameter [1]. The hypervelocity impact fragmentation of a stony body has been modeled [31], and the high strain rate fracture behavior of rock materials has been investigated [32]. A few experimental hypervelocity impact studies on brittle materials have been performed [33]. Under dynamic mechanical loading conditions, the fragment size of brittle materials is expected to decrease with increasing loading rate and with decreasing strength [32].

Considering the very limited meteorite mechanical property information that is available, generalizations concerning asteroid properties must be considered tentative at best. It is possible that Type M asteroids may be somewhat mechanically stronger than Type S asteroids, provided that neither is configured as a "rubble pile". However, whether an iron Type M asteroid might be more resistant to fragmentation than a stony Type S asteroid must be considered an open question. The ductile-to-brittle transition temperature of iron-nickel meteorites is close to the ambient average temperature of asteroids in space when they are in the vicinity of the Earth. Furthermore, high strain rate explosive or impact asteroid deflection methods could further lower this ductile-brittle transition temperature.

In the absence of any direct measurements of asteroid mechanical properties and behavior, the best course of action to minimize some of the uncertainty may be to evaluate the high strain rate mechanical behavior and hypervelocity impact behavior of asteroid/meteorite simulant materials under controlled laboratory conditions. The relatively large microstructural size of chondrules and Widmanstatten structures in meteorites is an important, but not insurmountable, issue for the synthesis and testing of simulants. In association with such an approach, comparisons of simulant material behavior to actual meteorite material behavior should be made, to the greatest extent that is feasible.

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