DIFFERENCES OF RELATIVE STRENGTH AMONG CHONDRITES MEASURED BY THE VIBRATIONAL FRACTURING RATE

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***Abstract*:** By using the vibrational fracturing rate method, differences of relative strength among H, L, LL and C chondrites are quantitatively measured. The relative strength is given by the value of $\log(V_0/V)$ where V_0 is the vibrational fracturing rate of single crystal calcite and V is that of the sample. Condrites studied are classified into two groups. One has values of $\log(V_0/V)$ between 0.8 and 1.2 and the other has the values less than 0.1. The former includes chondrites of types H4, H5, H6, L3, L4 and L5, and the latter includes L6, LL5, LL6 and the matrix of C3. The former group has higher metal content than the latter. The relative strength of L chondrites decreases from L3 to L6. This relation can be attributed to the loss of volatile material from grain boundaries or to the heterogeneous thermal stress distribution in chondrite parent bodies. The vibrational fracturing rate shows little correlation with porosity and density.

1. Introduction

Collision process is of importance for the evolution and brecciation of meteorite parent bodies and planetoides as well as for the impact cratering on the surface of planets and satellites. Fracture strength is one of the key properties in collision process (HARTMANN, 1969, 1978; MATSUI and MIZUTANI, 1977; GREENBERG *et al.*, 1978).

In the early stage of the solar system, intense lithification of these bodies seemed to have taken place. Chondrite parent bodies are estimated to be less than a few hundred kilometers in diameter, and chondrites did not experience intense remelting processes (*e.g.* WASSON, 1972, 1974; MINSTER and ALLEGRE, 1979; MIYAMOTO and

FUJII, 1980; MIYAMOTO *et al.*, 1980a). Although experimental studies on the strength of meteorites have been very few, chondrites are evidently lithified to some extent (WOOD, 1963; FUJII *et al.*, 1980, 1981a, b). Main purpose of this study is to find quantitative relations of the strength of chondrites with their chemical groups and petrologic types.

FUJII *et al.* (1980, 1981a) proposed a new strength measure named "the vibrational fracturing rate method", which is suitable for small rocks of high scarcity values such as extraterrestrial material. Their strength measure corresponded well with the relative hardness of single crystals (quartz, olivine, anorthite and calcite) and terrestrial rocks (basalt, serpentinite, pyrophyllite and talc). Only three ordinary chondrites (L3, L6 and LL6) were studied.

In this study, we apply this method to a wide variety of petrologic types of chondrites. The vibrational fracturing rates of 11 chondrites including H, L, LL and C chondrites are measured together with their density, porosity and metal content for the same samples.

2. Experimental Procedures

2.1. Vibrational fracturing rate measurements

The ground sample surface was excavated by using an ultrasonic machine under constant amplitude and frequency conditions. The vibration was transferred through a 2 mm-diameter steel rod to the sample surface. Water was continuously supplied to the sample surface in order to get a stable mechanical impedance condition. No grinding powder was used since fragments of the sample itself acted as grinding powder vertically hitting the sample surface within the water layer. The rate of excavation under a constant normal stress was measured by a differential transformer and recorded on a strip chart. The experimental procedures except the method of normal stress application were the same as those described in detail by FUJII *et al.* (1980). For application of the normal stress, a lever system was used in this study, instead of a spring in the previous study (FUJII *et al.*, 1980).

To ensure the reproducibility of measurements, the vibrational fracturing rates of calcite, olivine and quartz were measured for various values of normal stress (Fig. 1). These three single crystals were taken to be standard samples. A normal stress between 4 and 6 bars is suitable for wide-range measurements of the vibrational fracturing rate. When normal stress of more than 8 bars was applied to calcite, the vibrational fracturing rate of calcite became unmeasurably high (arrows in Fig. 1). Symbol F indicates that small tips of the surface of calcite were fractured and the measurement became unstable. In this study, normal stress of 0.5 ± 0.02 MPa (5.0 bars) was taken throughout the measurement.

Fragments of chondrites were embedded in resin and cut in the middle to make at least 5 mm $\times$ 5 mm flat sample surface. Excavation experiments were made several

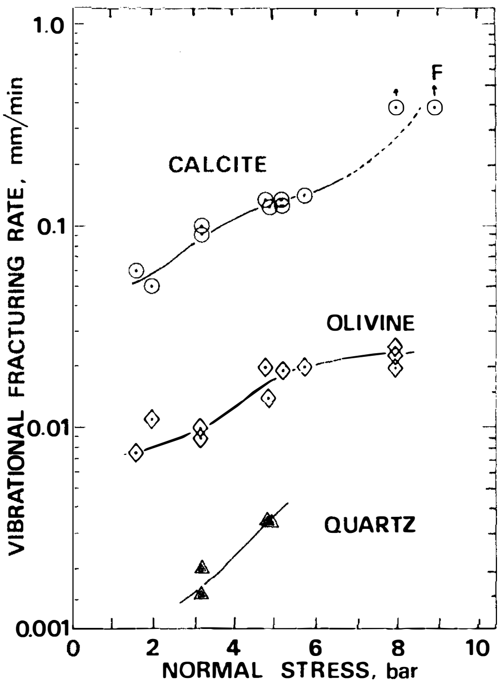


Fig. 1. Variation of the vibrational fracturing rate of single crystals against applied normal stress. Arrows indicate the occurrence of unmeasurably high rate of excavation. Symbol F indicates that small tips of the sample surface were fractured and the measurement becomes unstable.

times on one side of each sample. The other side of the sample surface was left for the metal content measurement. Several excavation rates were measured on a sample surface and the average rate was taken as the vibrational fracturing rate of the sample.

2.2. *Density and porosity measurements*

By using the Archimedean principle, density and porosity were mesured for a fragment of chondrite from the same specimen as that used for the vibrational fracturing rate measurement. The sample was weighed first in air, then the pore space of the sample was completely replaced by toluene in vacuum. The sample was weighed secondly in toluene and thirdly in distilled water. Because toluene is immiscible with water, water can not intrude into the pore space filled with toluene. Bulk and intrinsic (*i.e.* averaged grain) densities were estimated from the three weights by using the densities of toluene and distilled water. Accuracy of the obtained intrinsic and bulk densities was considered within a few percent because of the small sample size. For samples of less than 150 mg, small porosity values should be considered as crude estimates.

2.3. *Estimation of the metal content*

The unexcavated side of the sample surface was polished and used for estimation of the metal content by taking photographs under a microscope with reflected light. One photograph (7.3 cm × 9.5 cm) covered over 1.0 mm × 1.3 mm of the surface area. Fraction of the metal area was calculated by examining at least two photographs of different portion of each sample surface, and considered to be equal to the volume fraction (*i.e.* the homogeneous distribution of metal phase is assumed).

3. Results

Figure 2 shows examples of excavated depth versus time curve for chondrites and standard samples (olivine and calcite). An inclusion with about 2 mm-diameter is found in the border of the surface of Allende. Allende (m) and (i) in the figure indicate different portions of excavation in the same specimen. Excavated depth versus time curve of Allende (i) is obtained at the excavation location within a few milimeters distance from the center of the inclusion. The highest rate of excavation with large variation in the curve of Allende (m) is obtained in the other portion (matrix) of the specimen. It indicates that this portion is highly heterogeneous and loose. Small fragments are often removed from the excavated hole, suggesting the occurrence of intense fracture near the hole. In contrast, the curve of Allende (i) shows a smooth and low rate of excavation which is similar to that of olivine or ALH-77115 (H6). The curves of Y-75258 (LL6) and ALH-77231 (L6) show an intermediate rate of excavation. Single crystal of calcite with the excavation direction perpendicular to $r\{10\bar{1}1\}$

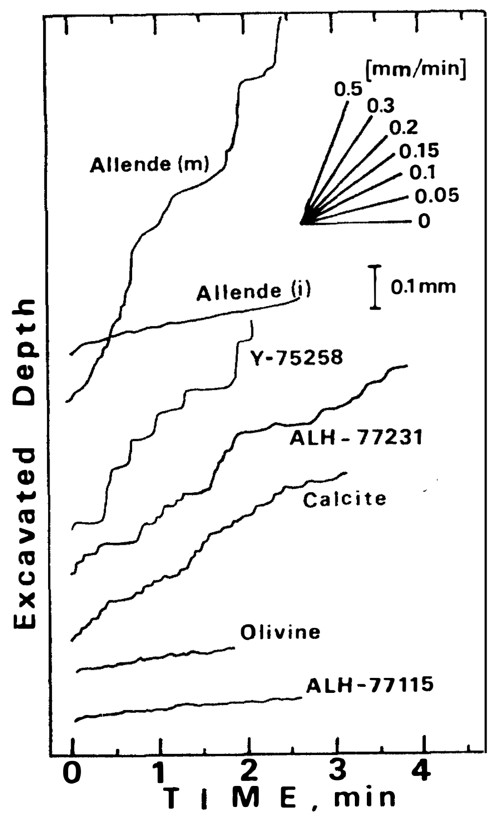


Fig. 2. Examples of excavated depth versus time curve for typical chondrites and standard samples.

shows a similar rate of excavation to that of ALH-77231. The vibrational fracturing rate is obtained as the time-averaged excavation rate. It is obvious that high rates of the vibrational fracturing are always associated with large fluctuation of excavation rates.

Vibrational fracturing rates obtained for each sample show relatively small variations within $\pm 10\%$ except for Allende (m), and are listed in Table 1. Three H chondrites show the lowest rate of vibrational fracturing among chondrites studied. This value is about half of that of olivine. No significant contrast is observed among H chondrites. In contrast, wide variations of the vibrational fracturing rate of L chondrites are obvious. Y-74191 (L3) has a similar rate of the vibrational fracturing to H chondrites and the lowest rate among L chondrites. The vibrational fracturing rate of L chondrites increases from petrologic type L3 to L6, although a large gap between L5 and L6 is observed. ALH-78105 (L6) shows unmeasurably high rate of excavation after a few minutes' experiment. Similar phenomenon is also observed for ALH-78109 (LL5) and Allende (m). The vibrational fracturing rate of two LL

Table 1. Vibrational fracturing rate (V.F.R.), density, porosity and metal content of chondrites.

	V.F.R.[1] (mm/min)	Density (g/cm^3) intrinsic	bulk	Porosity (%)	Metal content (vol %)	Remarks
Calcite[2]	0.135	2.72	—	—	—	⊥ar to $r\{10\bar{1}1\}$
Olivine[2]	0.019	3.30	—	—	—	
Quartz[2]	0.004	2.65	—	—	—	⊥ar to $c\{001\}$
ALH-77233	0.010_0	3.64	3.45	5	13	H4
ALH-77182	0.010_4	3.48	2.97	15	8	H5
ALH-77115	0.012	3.37	(3.11)[4]	(8)[4]	20	H6
Y-74191[2]	0.011	—	—	—	13	L3
ALH-77230	0.014	3.48	3.44	1	16	L4
ALH-77254	0.021	3.49	(2.88)	(18)	10	L5
ALH-77231[2]	0.110	3.48	(3.36)	(3)	5	L6
ALH-78105	0.225[3]	3.58	3.44	4	5	L6
ALH-78109	0.260[3]	3.39	2.72	20	8	LL5
Y-75258[2]	0.230	3.53	(2.38)	(33)	4	LL6
Allende (i)	0.040					
(m)	0.360–0.760[3]	3.64	2.68	26	—	C3

1) Values are obtained under normal stress of 0.50 MPa (5 bars).
2) Sample is the same specimen as that reported by FUJII *et al.* (1980).
3) V.F.R. becomes unmeasurably high after a few minutes' experiment.
4) Parentheses indicate less accurate data (specimen weight, <150 mg), uncertainty of bulk density is more than a few percent.

chondrites (Y-75258 (LL6) and ALH-78109) is similar to that of ALH-78105 (L6) and twice as high as that of calcite.

The values of intrinsic and bulk densities, porosity and metal content (vol%) are also listed in Table 1. Porosities of more than 20% are observed only in LL chondrites and C3 (Allende) chondrite. Ordinary chondrites containing metal phase of less than 8 vol% have the vibrational fracturing rate of higher than 0.1 mm/min, except ALH-77182 (H5). No correlation between intrinsic density and chemical group of chondrites is observed.

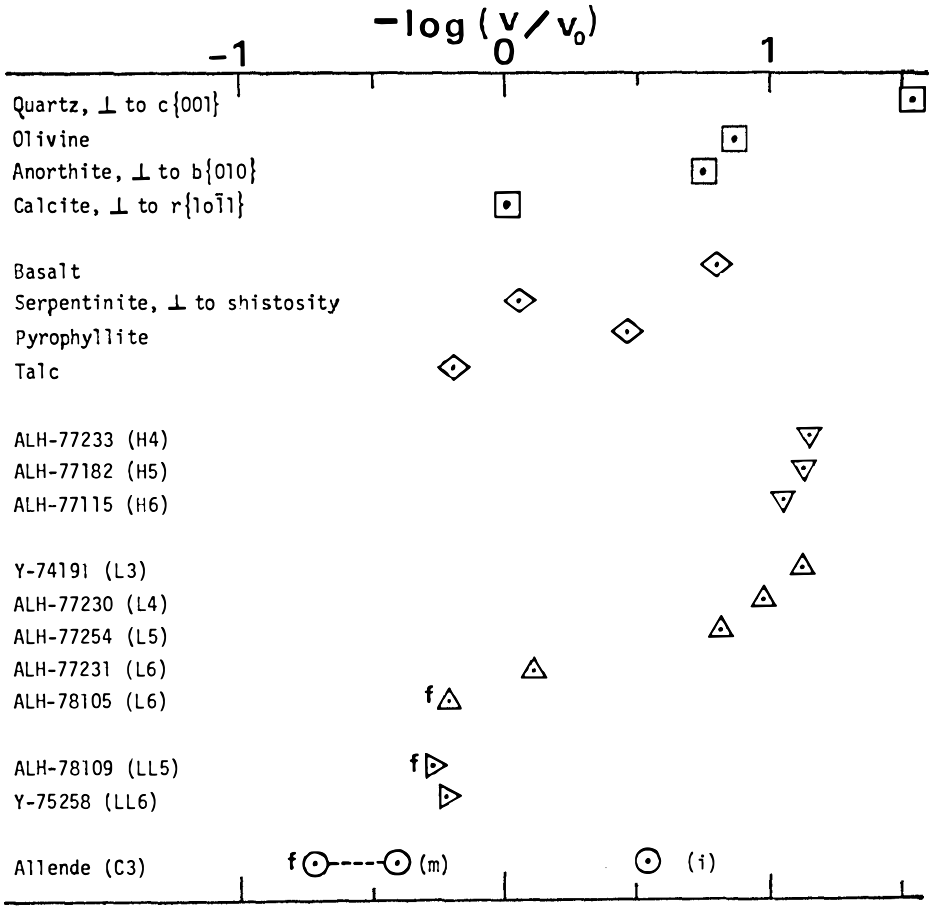
4. Discussion

Because the absolute value of the vibrational fracturing rate is affected by normal stress, size of tool tip, amplitude of vibration and mechanical impedance condition, only a relative value has its meaning. It is possible to extend this measure for a wider variety of the values of the vibrational fracturing rate of samples, referring to an appropriate standard sample and the diagram of normal stress variation (Fig. 1). As the values of the vibrational fracturing rate among chondrites studied range over nearly two orders of magnitude, it is convenient to take a logarithmic ratio of these values to that of appropriate standard. It is convenient also to reverse the ratio, because the larger the vibrational fracturing rate, the lower the strength. Figure 3 shows logarithmic ratios with a minus sign of the vibrational fracturing rate of the samples studied (V) to that of calcite (V_0). Data for anorthite, rocks and Allende are taken from previous studies (FUJII *et al.*, 1980, 1981a).

Though numbers of samples are limited, we temporarily assume in the following discussion that each chondrite sample is a representative of the respective petrologic type. As pointed out in the previous section, there are two groups according to the vibrational fracturing rate. One has the values of $\log(V_0/V)$ between 0.8 and 1.2, and the other has the values less than 0.1. The former includes L3 to L5 and all H chondrites, and the latter includes L6, C3 and LL chondrites. It is noted that olivine, anorthite and basalt samples are similar to the former while calcite, serpentinite and talc samples are similar to the latter.

It is plausible to consider that the presence of metal phase at inter-grain boundaries is a factor to control the vibrational fracturing rate of chondrites. Relatively higher strength of H chondrites in comparison to L and LL chondrites can be attributed to the amount of metal phase. In order to ascertain the effects of metal phase on the strength, it is needed to further investigate size and configuration distributions of metal phase at intergrain boundaries. Intrinsic and bulk densities correlate little with the vibrational fracturing rates. The effect of porosity is not certain because reliable data are scarce.

Differences of the vibrational fracturing rate among petrologic types are obvious in L chondrites. In contrast, such a clear difference is not observed either in H or



V_0= vibrational fracturing rate of Calcite.

Fig. 3. Logarithmic ratios, $-\log(V/V_0)$, *of the vibrational fracturing rate of samples* (V) *and that of calcite* (V_0). *Symbols of squares, diamonds, triangles and circles represent single crystals, rocks, ordinary chondrites and carbonaceous chondrites, respectively. Symbol f indicates the occurrence of unmeasurably high rate of excavation. Data for rocks, anorthite and Allende are taken from* FUJII *et al.* (*1980, 1981a*).

LL chondrites. The strength of chondrites represented by the inverse of vibrational fracturing rate is likely to depend on grain-to-grain adhesion and cementing condition between grains, besides the amount of metal phase. It appears that the presence of intergrain fine material causes a significant increase in adhesive strength of chondrites. The adhesive strength of loosely consolidated aggregates increases largely by adding small amounts of low melting-temperature, hydrous and amorphous fine grains such as ice, serpentine and glass (FUJII *et al.*, 1979, 1980, 1981b; MIYAMOTO *et al.*, 1980b). The strength of L chondrites shows the highest value for L3 and it decreases as the degree of thermal metamorphism increases from L3 to L6. This is contrary to an expectation that the degree of lithification increases as thermal metamorphism advances.

Formation process of petrologic types from 3 to 6 in chondrite parent bodies is considered to be thermal metamorphism by either internal heat source (MINSTER and ALLEGRE, 1979; MIYAMOTO *et al.*, 1980a, 1981) or external heat source (WASSON, 1972, 1974; MIYAMOTO and FUJII, 1980). The observations of grain boundaries by a scanning electron microscope for Y-74191 (L3) and ALH-77231 (L6) support the idea that the petrologic types are produced by thermal metamorphism (FUJII *et al.*, 1980). It is likely that volatiles were released from grain boundaries and from dehydration of hydrous minerals as thermal metamorphism advances. The decrease of strength with advance of petrologic type from 3 to 6 of L chondrites may be explained by the loss of volatiles (N. ONUMA, private communication, 1981).

There may be another possibility of explaining the relation between the strength and the petrologic type. Considerably strong thermal stress was possibly generated within chondrite parent bodies (Y. HAMANO, private communication, 1981; FUJII *et al.*, 1981b, c). Chondrites of different petrologic types experienced different thermal history and were lithified under probably different thermal stress. The decrease of strength from L3 to L6 might represent differences of thermal stress under which they were lithified. The relation might be useful for estimating the thermal history of chondrite parent bodies.

The problem to what extent the vibrational fracturing rate of fragment samples actually represents chemical groups or petrologic types of chondrites, remains unsolved. Effects of shock and fragmentation history and implantation of fine particles may differ for each chondrite and its parent body. In order to estimate bulk mechanical properties from experimental studies for fragments of chondrite samples, it is absolutely necessary to investigate the heterogeneity such as inclusion to matrix ratio, grain size distributions, etc. For example, if the grains larger than a few millimeters such as chondrules are sparsely distributed, the vibrational fracturing rate would be high for the matrix and low for the large grains. Bulk properties such as elastic constant, intrinsic and bulk densities and porosity may be influenced considerably by the ratio of inclusion to matrix. This may be the case for the Allende sample. Allende (i) would be olivine-rich chondrules, showing a slightly lower value of $\log(V_0/V)$ than that of olivine single crystal. However, the vibrational fracturing rate for the bulk of Allende would be represented by that of the matrix, Allende (m).

Results obtained in this study seem to be concordant with the hitherto qualitatively expressed experiences of meteorite researchers that type-3 chondrites are brittle or that H chondrites are harder than L, LL and C chondrites (N. ONUMA and A. MASUDA, private communication, 1981). It is desired to make further investigations of different petrologic types and chemical groups of chondrites together with the effects of intergrain fine materials on the mechanical properties of chondrites.

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