ON THE SHAPE OF Fe-Ni GRAINS AMONG ORDINARY CHONDRITES

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***Abstract*:** The irregular shape and anisotropic orientation of Fe-Ni grains are quantitatively described in eight ordinary chondrites from Antarctica. The chondrites studied include three H types: ALH-77233 (H4), ALH-77182 (H5) and ALH-77115 (H6); four L types: Y-74191 (L3), ALH-77230 (L4), ALH-77254 (L5) and ALH-78105 (L6) and one LL type: Y-75258 (LL6). The axial ratio (b/a), where a and b are the longest and semi-major axial lengths respectively, the area (S), and the circumferencial length (l) with appropriate divider opening (d) are measured for each Fe-Ni grain. The orientation distribution of the longest axis indicates that L chondrites are more anisotropic than H chondrites, though the number of grains is limited. The shape parameter defined by $l/\sqrt{S}$ is used as a quantitative indicator for the shape irregularity of Fe-Ni grains. Though the value of the shape parameter depends on d, it increases with the area for each chondrite with a fixed d of 0.01 mm. The fractal dimension is estimated by $-(\log N)/(\log d)$, where N is the number of segments for circumferencial length and d is varied from 0.01 mm to 0.15 mm. The fractal dimensions thus obtained for several grains in H4, H6, L4 and L6 chondrites are all about 1.4 and do not appreciably differ from each other. It means that the irregularity of the shape of Fe-Ni grains is self-similar in the range of d used. The average value of the shape parameter (S. P.) for each sample is defined as $l/(n\times\Sigma S)^{1/2}$, and appears to decrease with the increase of petrologic types from 4 to 6 for both H and L chondrites. The value of S. P. and the volume fraction of Fe-Ni grains correspond more or less well with the strength represented by the vibrational fracturing rate measurements (FUJII *et al.*, Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 362, 1981).

1. Introduction

Chondrites have not experienced intense remelting processes in parent bodies, which have evolved through the accretion of mutually colliding planetesimals (SAFRONOV 1969; HARTMANN, 1969; WASSON, 1974; SMITH, 1982). As planetesimals are loosely consolidated aggregates of silicate and metal grains in the early stage of their growth process, the degree of lithification has increased in the evolutional history of chondrites (SHORT, 1966; ASHWORTH and BARBER, 1976; FUJII *et al.*, 1978; HARTMANN, 1978). From the low-velocity impact experiments on loosely consolidated aggregates, signifi-

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cant increases of consolidation are observed when minor components with sticking properties between grains exist. Such minor components are once melted and sucesively frozen low melting-temperature material (*e.g.* ice) and easily deformed or recrystallized amorphous materials (*e.g.* fine-grained and glassy matrix) as demonstrated by MIYAMOTO *et al.* (1980) and FUJII *et al.* (1979, 1981b).

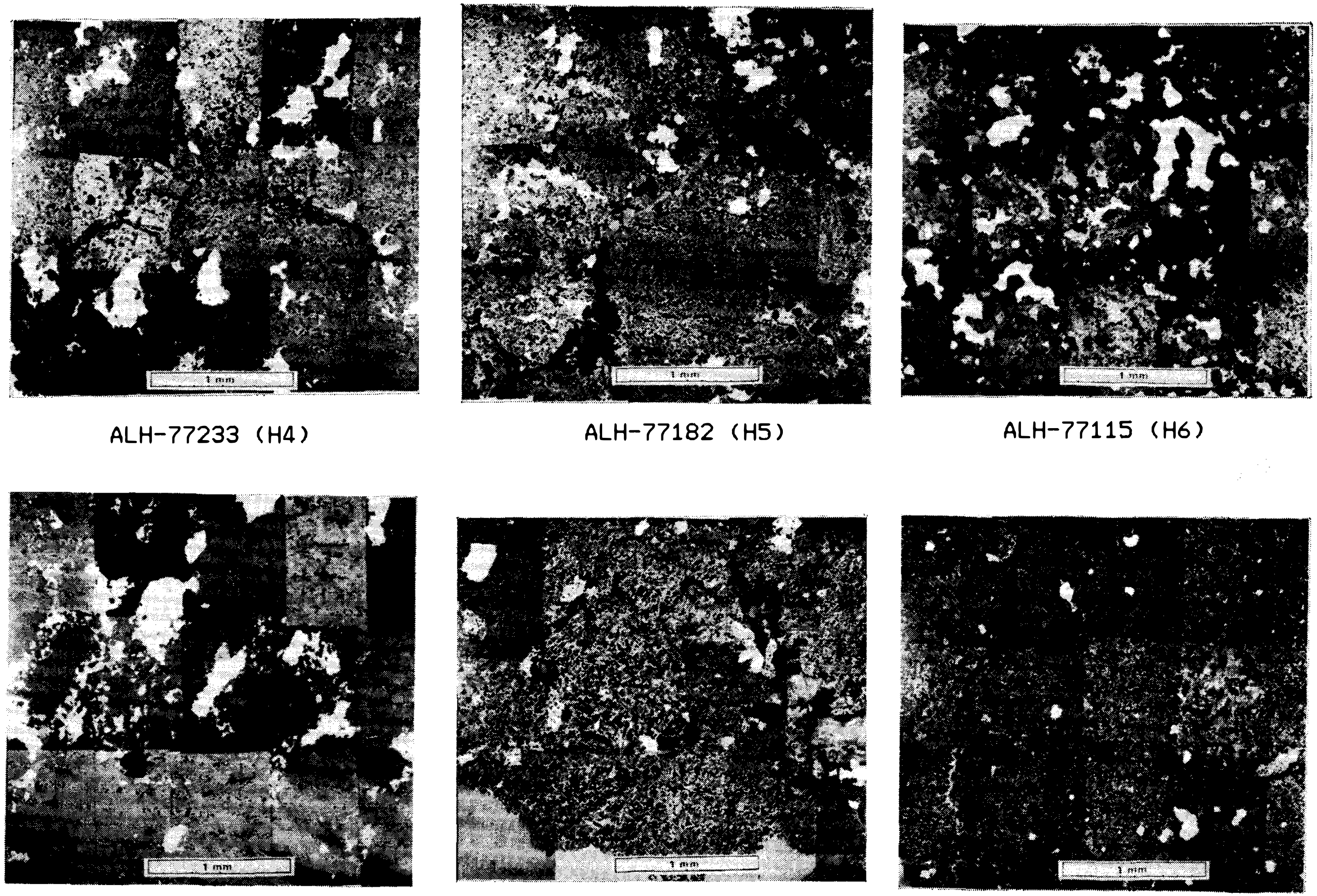
The presence and nature of the intergrain materials, such as pore-filling deformed or recrystallized matrices, would have strong influence on the mechanical properties, especially the strength, of chondritic aggregates (FUJII *et al.*, 1980, 1981a, d). Anisotropic orientation of chondrules (DODD, 1965, 1976a; MARTIN *et al.*, 1975; MARTIN and MILLS, 1978, 1980) and petrofabric analysis of silicate minerals (DODD and TELEKY, 1967; DODD, 1969b; KUMAZAWA *et al.*, 1981) suggest foliation anisotropy. The magnetic anisotropy in susceptibility also indicates foliation of metallic minerals (STACEY *et al.*, 1961; WEAVING, 1962; HAMANO and YOMOGIDA, 1982; SUGIURA and STRANGWAY, 1982). These anisotropies in chondrites could provide information about the mechanical situation of chondritic parent bodies.

The most important information provided by metallographic studies is the cooling rate in the approximate temperature range of 800–600 K (*e.g.* WOOD, 1967, 1979; HUTCHISON *et al.*, 1980; CHRISTOPHE MICHEL-LÉVY, 1981). Metal grains and rock-forming minerals in chondrites are more or less deformed or recrystallized and bonded together to some extent (DODD, 1969a, 1976b; BEVAN and AXON, 1980; SCOTT and RAJAN, 1981). The complex texture of metal grains may provide some clues for a long history ranging from thermal metamorphism in parent planetesimals during and after the aggregation to shock-induced metamorphism in the fragmentation process (WOOD, 1963, 1979; WASSON, 1972, 1974; DODD, 1976b). The texture of metal grains, such as the irregular shape and anisotropic orientations could also provide some information about the degree of lithification or other mechanical properties as well as the evolutional process of chondritic parent bodies (FUJII *et al.*, 1981c; HAMANO, 1982).

The volume fraction and the shape of Fe-Ni grains in ordinary chondrites are of importance to characterize the strength of grain to grain adhesion. In this respect, H, L and LL chondrites are chosen and the shape of Fe-Ni grains is quantitatively measured for the same specimen as used in the measurements of the strength by the vibrational fracturing rate (V.F.R.) method (FUJII *et al.*, 1980, 1981a).

2. Samples and Method of Measurement

All samples studied are from Antarctica and their strength has already been measured by the V.F.R. method (FUJII *et al.*, 1980, 1981a). They are three H chondrites: ALH-77233 (H4), ALH-77182 (H5) and ALH-77115 (H6); four L chondrites: Y-74191 (L3), ALH-77230 (L4), ALH-77254 (L5) and ALH-78105 (L6) and one LL chondrite: Y-75258 (LL6). As each chondrite sample belongs to a different petrologic type, hereafter we can tentatively refer to each chondrite by petrologic type without confusion. Samples were embedded in resin and cut to obtain at least 20 mm^2 of flat surface. The surveyed area was about 2.7×3.5 mm for each surface. By taking a photograph ($\times 100$) of the polished surface with reflected light, the area and the axial ratio (b/a) of each metal grain were measured, in which a and b were respectively the longest



ALH-77233 (H4) ALH-77182 (H5) ALH-77115 (H6)

ALH-77230 (L4) ALH-78105 (L6) Y-75258 (LL6)

Fig. 1. Examples of the surveyed surfaces of chondrites. White grains are metal phases in reflected light. FeS grains are slightly greyish.

and semi-major axial lengths. To investigate anisotropic orientation of the longest axis, three mutually perpendicular surfaces were surveyed for H4, H6, L4 and L6 chondrites. The orientation of the longest axis for each grains was measured by referring to an arbitrarily fixed coordinate in each surface. The accuracy in the determination of orientations depends on the axial ratio and varies approximately from $\pm 5°$ for (b/a) <0.5 to $\pm 15°$ for $(b/a)>0.7$.

The circumferencial length was also measured by using a divider opening of 1 mm (*i.e.* 0.01 mm in real scale). The metal grains with characteristic length of less than 0.05 mm and FeS grains were omitted in this measurement. Examples of the surveyed surfaces are shown in Fig. 1, in which white grains are metal phases. Under reflected-light microscopy, Fe-Ni grains can easily be distinguished from FeS grains, which are slightly darker and yellowish.

3. Results

3.1. Size and orientation of Fe-Ni grains

The curves of cummulative number *vs.* the area of Fe-Ni grains are shown in Fig. 2. Three H chondrites have relatively continuous distribution of the area and similar gradients to each other, whereas Y-74191 (L3) has one large Fe-Ni grain and Y-75258 (LL6) has no large one, as seen in Figs. 1 and 2.

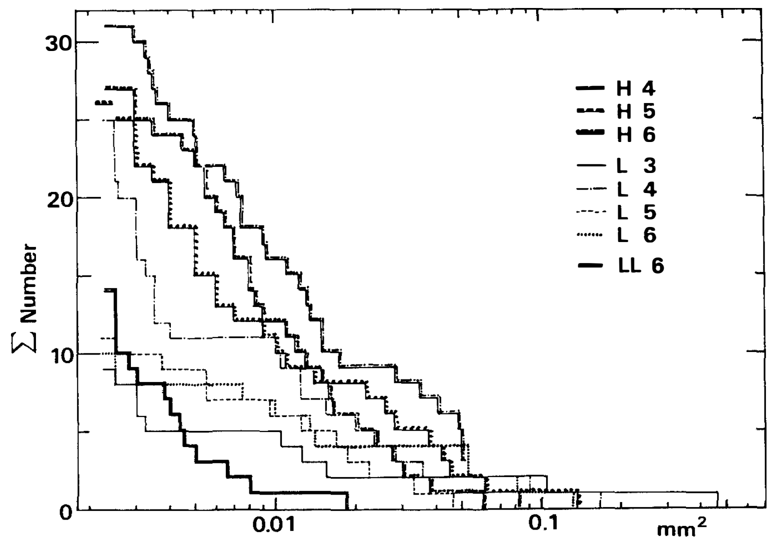


Fig. 2. Cummulative number vs. the area (abscissa) of Fe-Ni grains for each surface of the chondrites. The respective petrologic types correspond the Antarctic chondrites as listed in Table 1.

The distribution of the axial ratio for each type of chondrite is shown in Fig. 3. Larger values of (b/a) do not apparently correspond to the smaller area of Fe-Ni grains. The orientation distribution of the longest axis is illustrated in Fig. 4, in which the radial distance (r) is proportional to $(1-b/a)$, as indicated in the bottom of Fig. 4. Open circles and small dots represent the area of Fe-Ni grains larger and smaller than 0.01 mm^2, respectively. It appears likely that more rounded Fe-Ni grains exist in type 6 for both

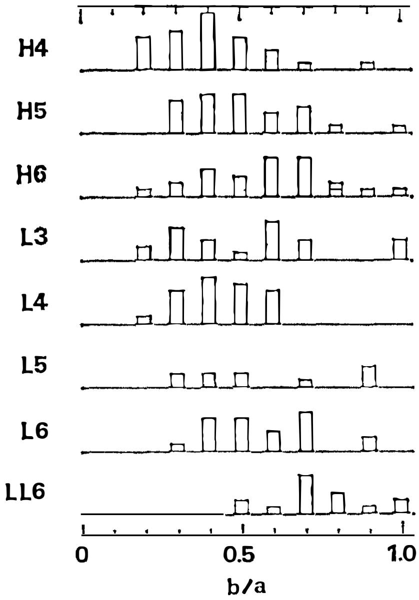


Fig. 3. Distribution of the axial ratio (b/a). Vertical scale is proportional to the number frequency.

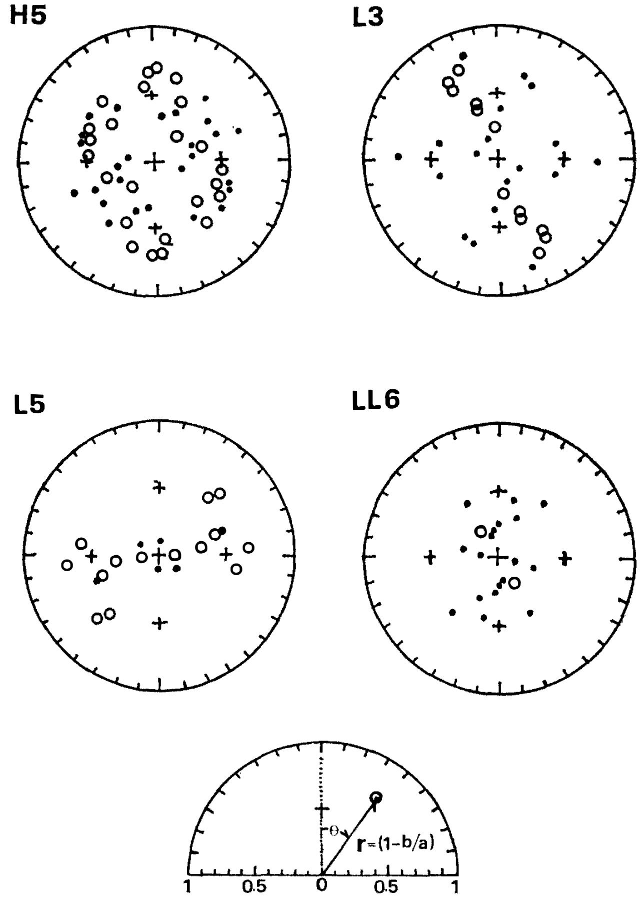


Fig. 4. Orientation distribution of the longest axis (a) for ALH-77182 (H5), Y-74191 (L3), ALH-77254 (L5) and Y-75258 (LL6). The radial distance (r) is proportional to 1−b/a, as indicated in the bottom diagram. Origin of coordinate is arbitrary. Open circles and dots represent the area of Fe-Ni grains larger and smaller than 0.01 mm, respectively.

H and L chondrites, especially in LL6. Although the number of Fe-Ni grains studied is limited, anisotropic orientations of these grains are more clear in L3 and L5 than in H5 and LL6, as seen in Figs. 3 and 4.

Figure 5 shows orientation distribution of the longest axis for four chondrites in three mutually perpendicular surfaces. Surfaces A, B and C are arbitrarilly named. Arrows with small labels indicate the direction normal to the adjacent surface. Large and small open circles correspond the area of Fe-Ni grains larger and smaller than 0.01 mm^2, respectively. It does not seem obvious whether the anisotropies in these chondrites are actually foliation or lineation. It may be partly due to the limited number of grains studied and to the dependency of the mean orientation anisotropy on the axial ratio and the area of Fe-Ni grains, unlike the nearly equal size and shape of chondrules (DODD, 1965; MARTIN and MILLS, 1978).

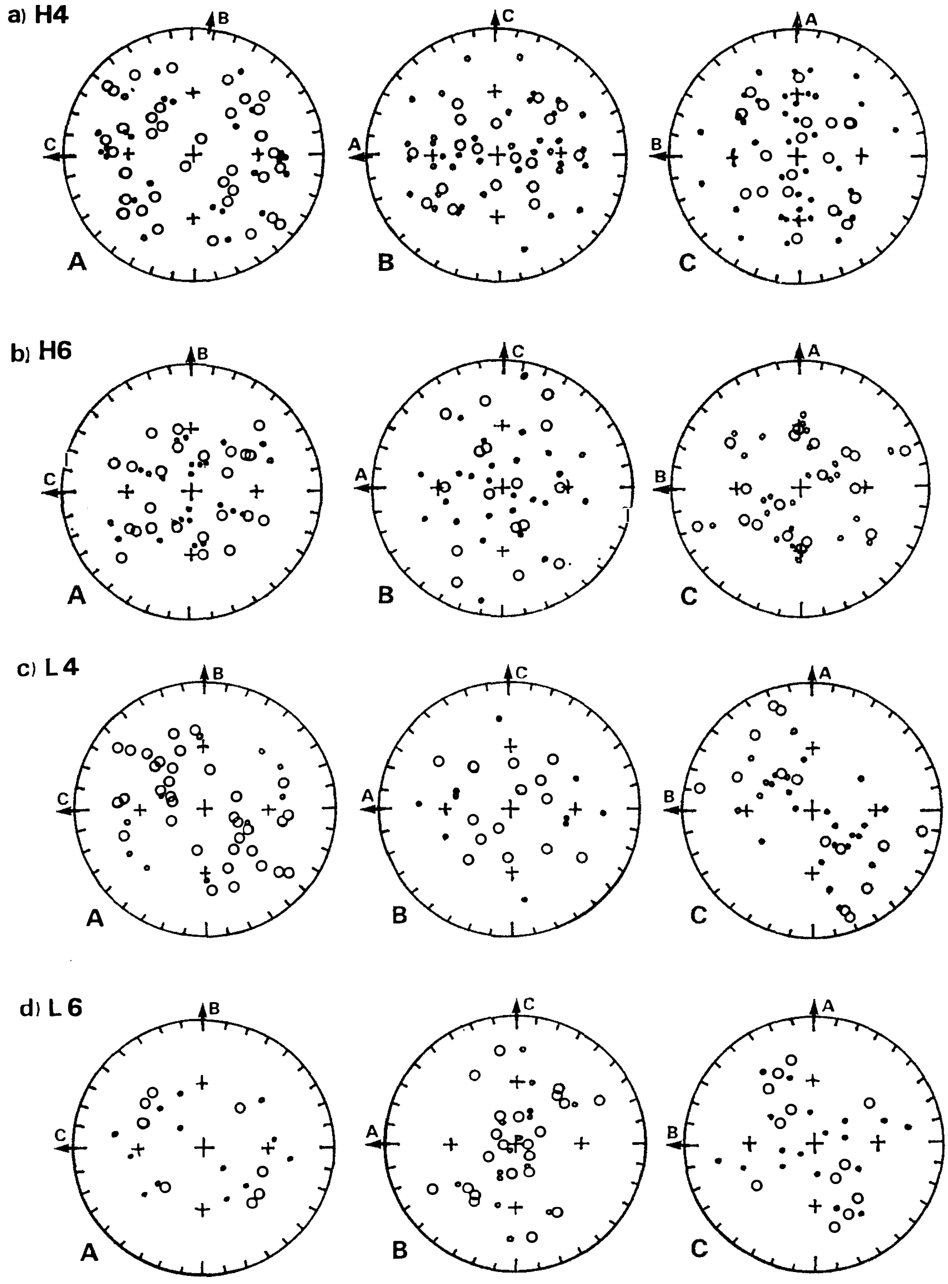


Fig. 5. Orientation distribution of the longest axis for four chondrites: a) ALH-77233 (H4), b) ALH-77115 (H6), c) ALH-77230 (L4) and d) ALH-78105 (L6). Surfaces A, B and C are arbitrarily taken but are nearly normal to each other. Arrows with small labels indicate the direction normal to the adjacent surface. Other symbols are the same as in Fig. 4.

3.2. *Shape parameter of Fe-Ni grains*

The ratio $l/\sqrt{S}$ is used to represent the shape irregularity of each Fe-Ni grain, where l is the circumferencial length and S is the area, and is hereafter referred to the shape parameter. The shape parameter is independent of the units of measurement but depends on the divider opening used. Distribution of the shape parameter for each chondrite is shown in Fig. 6, by tentatively using a divider opening of 0.01 mm. It is noticed that the mean value of the shape parameter decreases from type 4 to type 6

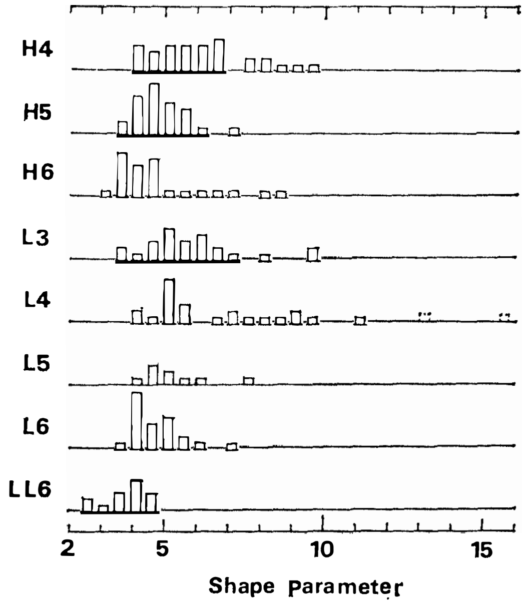
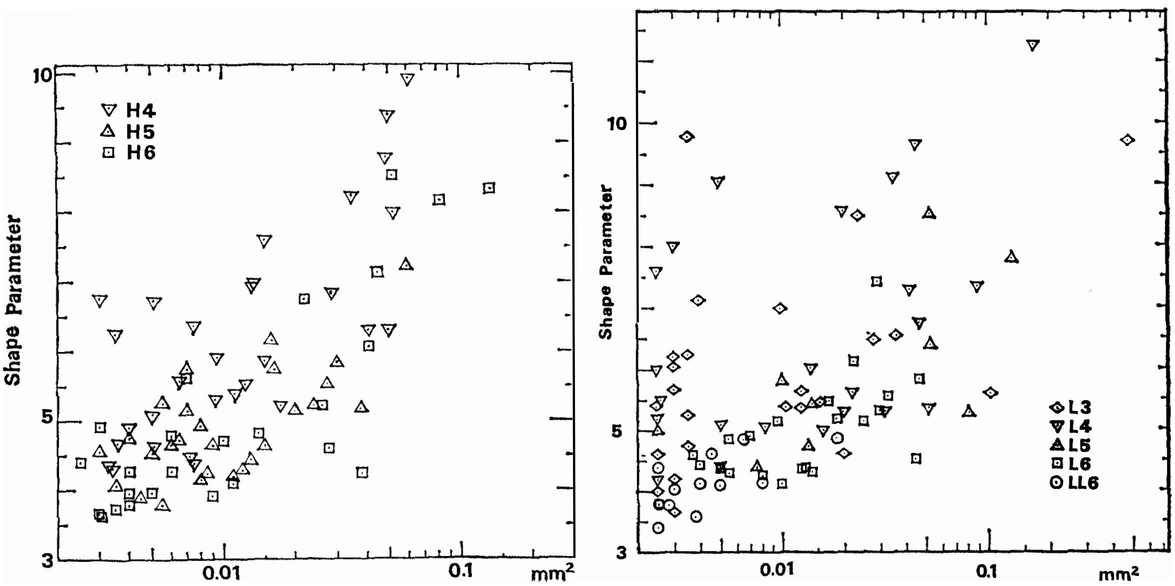


Fig. 6. Distribution of the shape parameter. Vertical scale is proportional to the number frequency.



(*a*) (*b*)

Fig. 7. The shape parameter vs. the area (abscissa) of Fe-Ni grains for a) H chondrites and b) L and LL chondrites.

both in H and L chondrites. This may indicate that the shape irregularity of Fe-Ni grains decreases as thermal metamorphism advances.

Figures 7a and 7b respectively show the shape parameter *vs.* the area of Fe-Ni grains for H and L chondrites. It is evident that grains with larger values of the shape parameter tend to have larger area, for both H and L chondrites. As the number and sizes of Fe-Ni grains differ for each chondrite, the circumferential length and the area are summed and the ratio is normalized by square root of the number (n) of grains, *i.e.* $l/(n\times \Sigma S)^{1/2}$. This extent can be considered as an average shape parameter (S. P.), which could represent an average irregularity of the shape of Fe-Ni grains for each

Table 1. The volume fraction, the average shape parameter (S. P.), and the axial ratio (b/a) of Fe-Ni grains.

Sample	Fe-Ni grains (vol.%)	Fe-Ni grains S.P.	Fe-Ni grains (b/a)	$-\log(V/V_0)$	Porosity (%)	Remark
ALH-77233	6.3	6.0	0.41	1.13	5	H4, A
ALH-77182	4.1	4.7	0.52	1.11	15	H5
ALH-77115	4.9	4.6	0.59	1.05	(8)	H6, A
Y-74191	7.1	4.6	0.58	1.09	—	L3
ALH-77230	8.8	6.3	0.44	0.98	1	L4, A
ALH-77254	4.0	5.2	0.59	0.52	18	L5
ALH-78105	2.3	5.0	0.61	0.09	4	L6, A
Y-75258	0.9	3.7	0.74	−0.23	(33)	LL6

1) The logarithmic ratios of the V.F.R. and porosities are from FUJII *et al.* (1980, 1981a).
2) Values of porosity in parentheses are less reliable, because of small specimen sizes.
3) Symbol A in the remark column corresponds to the surveyed surface in Fig. 5.

chondrite. Volume fraction of Fe-Ni grains is assumed to be equal to the area fraction, and listed in Table 1, together with the S. P. and the average value of (b/a).

4. Discussion

As reviewed by DODD (1965), the mechanisms by which the fabric of chondrites could have been established include estimation from the accretion of fluid medium onto a planetesimal or parent body, alignment by solar fields during aggregation, thermal metamorphism in a hot parent body, and shock-induced metamorphism. There seems, however, no fundamental agreement whether the processes during which Fe-Ni grains have deformed or recrystallized increase the irregularity of their shape or not (DODD, 1965, 1969a; WASSON, 1974).

In the evolutional accretion stage of chondrite parent bodies, there would be sufficient intergrain spaces which Fe-Ni grains could occupy as the recrystallization and deformation proceeded. In such a case, the irregularity of the shape of Fe-Ni grains would increase with their deformation and the orientation of these grains would be more anisotropic (increase of foliation), as noted by FUJII *et al.* (1981c) and HAMANO (1982). In contrast, the shape of Fe-Ni grains would become less irregular by the thermal effect because the thermal metamorphism would make the surfaces of these grains rounded and smooth, if the stress was not appreciably effective. The distribution of (b/a) and the shape parameter may reflect this effect, as seen in Figs. 3 and 6. As the degree of lithification could increase by shock-induced metamorphism (SHORT, 1966; ASHWORTH and BARBER, 1976), the shape of Fe-Ni grains would become irregular. However, the shock-induced deformation would not be responsible for establishing the foliation anisotropy in chondrites, because of short duration and high stress in the collision and disruption process of chondrite parent bodies (HAMANO, 1982).

The foliation in chondrites is generally observed in various properties: anisotropic orientations of the magnetic susceptibility (STACEY *et al.*, 1961; WEAVING, 1962; HAMANO and YOMOGIDA, 1982; SUGIURA and STRANGWAY, 1982), orientations of the longest axis of chondrules (DODD, 1965, 1976a; MARTIN *et al.*, 1975; MARTIN and MILLS, 1978, 1980), and petrofabric analysis of silicates (DODD and TELEKY, 1967; DODD, 1969b; KUMAZAWA *et al.*, 1981). The degree of foliation seems independent of the degree of recrystallization (*i.e.* of petrologic type) and of porosity (HAMANO and YOMOGIDA, 1982). The establishment of foliation could be a result of uniaxial compression and thus appears to have been established during accretion of parent bodies (HAMANO, 1982). But it depends sensitively on the structure and physical properties of material as well as the physical conditions. As seen in Fig. 1, however, the actual shape of Fe-Ni grains is too complex to be represented by a simple ellipse, the orientation distribution of the longest axis may not be an appropriate indicator for the anisotropy corresponding to magnetic one in average (Figs. 4 and 5). Systematic investigations for various properties are obviously needed to disclose the mechanism of anisotropic orientation distributions in chondrites.

Metal and sulfide phases are generally absent from silicate chondrules and occur as grains with irregular outlines for all the samples studied. Figures 1 and 2 show that exceptionally large metal grains exist in the types 3 and 4 L chondrites. However, these large grains are not rounded, in contrast to the observations of HUTCHISON *et al.* (1980) and the shape parameters are large, as seen in Fig. 7. They may reflect partial to complete crystallization or deformation to fill the available spaces, even though they may have originally formed rounded droplets during the aggregation process of chondrites. Although the shape parameter introduced in the previous section depends on a divider opening (d), a more useful indicator of the complexity of the irregular shape of these grains would be the fractal dimension (MANDELBROT, 1977), which is independent of d.

The fractal dimension D is defined by $-(\log N/\log d)$, in which the circumferencial length is represented by the number of segments (N) with a divider opening of d. As demonstrated by MANDELBROT (1977) and BURROUGH (1981) for landscapes and other environmental data, the value of D would be useful for trying to separate scales of variation that may be the result of particular natural processes, for example, deformation and recrystallization processes which could cause the complex shape of Fe-Ni grains.

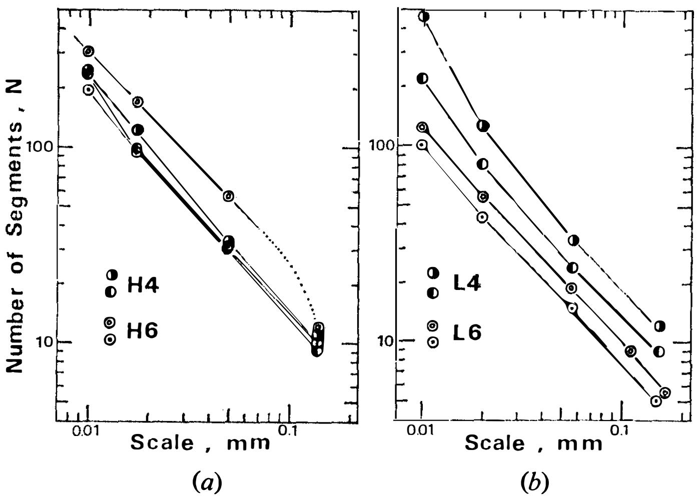


Fig. 8. The circumferencial length represented by the number of segments (N) vs. the scale of divider opening. Examples are from a) H4: ALH-77233 and H6: ALH-77115 (left), and b) L4: ALH-77230 and L6: ALH-78105 (right). The fractal dimension (MANDELBROT, 1977) can be calculated from the gradient of this diagram.

Figures 8a and 8b show the log N *vs.* log d plots for some Fe-Ni grains from ALH-77233 (H4), ALH-77115 (H6), ALH-77230 (L4) and ALH-78105 (L6). The values of D for these examples are about 1.4, and do not differ significantly from each other. This suggests that the shape irregularity of Fe-Ni grains is self-similar in the range of d studied. The estimation of D is obviously desirable to extend to other minerals as well as to the smaller values of d. Further investigation is needed to deduce some conclusions from this preliminary measurement.

Fe-Ni grains in Y-75258 (LL6) have the value of S. P. similar to that of a circle (3.545). This is partly because the size of irregularity and/or grain itself is comparable or smaller than the divider opening used, whereas for ALH-77182 (H5), ALH-77115 (H6) and Y-74191 (L3), the shape of Fe-Ni grains is in average similar to that of a regular triangle (4.560). Though the number of samples is limited, the values of S. P. appear to decrease with the increase of petrologic types from 4 to 6 for each chemical group of chondrites. This tendency may indicate that the shape of Fe-Ni grains becomes rounded as the thermal metamorphism advanced. In spite of the limited area of surveyed surfaces, the value of S.P. and the volume fraction of Fe-Ni grains correspond more or less well with the strength represented by the V.F.R. measurements by FUJII *et al.* (1980, 1981a), except for ALH-78105 (L6). It is, however, noticed that the volume fraction of Fe-Ni grains does not always correspond to total metallic Fe content and is merely one of the factors to influence the strength of chondrites (MIYAMOTO *et al.*, 1980; FUJII *et al.*, 1981a).

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