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HARDNESS ANALYSIS OF METALLIC PARTICLES IN ORDINARY CHONDRITES

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Abstract: Mechanical properties of metallic particles in four shock-melted and seven unshocked ordinary chondrites were studied by means of the Micro Vickers Hardness Measurement. Together with the morphological and mineralogical properties, they were used to characterize the shock effects in the chondrites. Average value of hardness in Fe-Ni particles is smaller (less hard) than that of troilite. Average values of hardness of taenite particles in Y-790964 (LL) and Y-75258 (LL6) are 144 and 348 kg/mm^2, respectively. The hardness increases as the Ni content increases. However, the range of hardness values in Fe-Ni particles shows little systematic changes with the petrologic type. The fractal dimension of two-dimensional shape of metallic particles was measured by the personal-computer-aided image processing system. The Vickers hardness varies in some systematic way. In shock-melted LL chondrites, when the amount of vesicles increases, the average of hardness decreases. Shock effects are heterogeneous even on a microscopic scale, and irregular grains (with higher values of the fractal dimension) seem to show shock effects more strongly.

1. Introduction

Shock effects recorded in meteorites have been described by mineralogical and petrochemical characteristics, such as undulation of plagioclase and olivine grains (*e.g.*, DODD, 1981) and the hardness of metallic grains (SEARS *et al.*, 1984). Although these effects are characteristic to the results of shock experiments, it is likely that most of shock effects in porous and mechanically heterogeneous samples are inhomogeneous in microscopic observations. FUJII *et al.* (1980, 1981) proposed a new method called the Vibrational Fracturing Rate (VFR) method for describing the bulk strength (about 2 mm in diameter). The VFR is a good method to estimate a degree of lithification of samples. Shock effects may increase the lithification of meteorites due partly to the 'gluing effects' of silicate melts and/or deformable metallic particles filling the grain boundaries, and due partly to the 'fragmentation effects' of silicate and metallic grains by polygonization, pileup of dislocation, and so on. For example, shock-melted LL chondrites (Y-790964, Y-790723, Y-790519) show similar strength to that of single crystal quartz, while unshocked LL chondrites (ALH-78109 (LL5), Y-75258 (LL6)) show less strength in terms of the VFR values (MIYAMOTO *et al.*, 1982). In this paper, we intended to obtain quantitative parameters of shock effects in the metallic particles of ordinary chondrites, and we focused our attention on (1) the mechanical properties of metallic particles by measuring Vickers hardness number, (2) fractal dimension of the two-dimensional shape, and (3) elemental composition such as Ni content.

2. Experimental

Eleven Antarctic ordinary chondrites were used in this study: four shock-melted chondrites Y-82163 (H6.5), Y-790964 (LL), Y-790519 (LL), Y-790964 (LL), and seven unshocked chondrites ALH-77233 (H4), ALH-77115 (H6), Y-74191 (L3), ALH-77230 (L4), ALH-77254 (L5), ALH-77231 (L6), Y-75258 (LL6). Although all meteorites found on the earth are shock-experienced, we used the term 'shock-melted' or 'unshocked' according to the presence or absence of maskelynite (plagioclase-rich glass embedded in grain boundaries). All samples are soaked in resin and cut to the shape of a rectangular prism with at least one surface area of it greater than 25 mm^2. Figure 1 is a sketch of the polished surface of Y-790964 (LL), in which dark parts represent vesicles. Sizes of these vesicles are far larger than those of silicate and metallic grains, which suggests a strong shock on porous or gas-rich chondrites and abundant vesicles are presumably produced by vaporization and decomposition of FeS during shock heating (MIYAMOTO *et al.*, 1984; TAKEDA, 1988). By using the image processing system, the percentages of vesicles in shock-melted LL chondrites were obtained; 26% in Y-790964, 21% in Y-790519, and 6% in 790345, which were consistent with the observation by SATO *et al.* (1982).

The hardness analyses for iron meteorites have been made and summarized (*e.g.*,

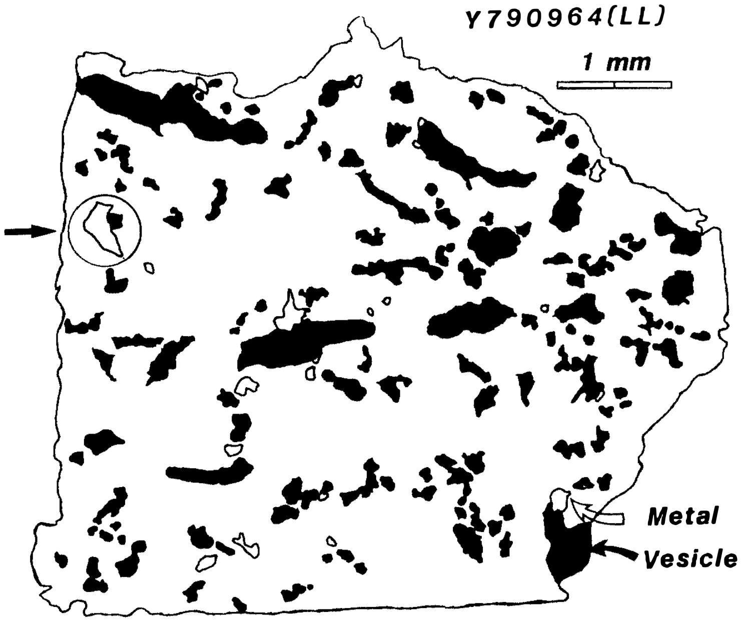

Fig. 1. A sketch of polished surface in Yamato-790964 (LL) indicating the distribution of vesicles. Black parts are vesicles, which account for about 26% of total area. Grain boundaries of metallic grains are also shown.

Buchwald, 1975), but measurements of metallic particles in stony meteorites were very scarce (*e.g.*, Sears *et al.*, 1984). The micro Vickers hardness measurement is one of the hardness determinations by indentation of diamond. The Vickers hardness (H_V) is given as (Westhrook and Conrad, 1973),

$$H_V = W/A_c \tag{1}$$

where W is a weight added to the sample surface through the diamond, and A_c is the area of the contact between the diamond and the surface (Fig. 2). By checking reproducibility and crack-less indentation results, we selected 10 grams for an optimum W, and 15 seconds for weighting duration, then A_c in kg/mm^2 can be calculated as,

$$A_c = d_1^2 \sin(136°/2)/0.2 \tag{2}$$

where d_1 is the diagonal length in microns of square-shaped indentation (Fig. 2). The angle of 136 degrees is the edge angle of the diamond. Under these conditions, d_1 ranges from a few to about 10 microns, so that our measurement reflects the hardness of a flat surface area of about 10 microns wide. Figure 3 shows an example of results for Fe-Ni grain in ALH-77230 (L4). The diagonal length, d_1, was measured, as an average of two diagonal lengths, on the enlarged optical microscopic photograph

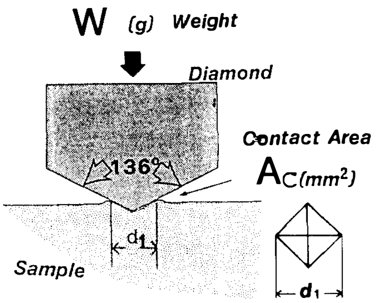

Fig. 2. Schematic diagram of the micro Vickers hardness measurements.

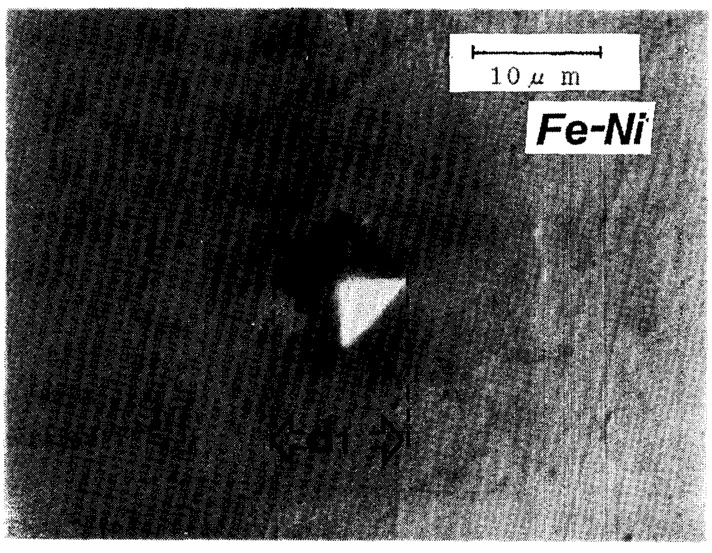

Fig. 3. Optical microscopic photograph with reflected light for measurements of d_1 in the Vickers hardness testing on Fe-Ni grains (ALH-77230 (L4)).

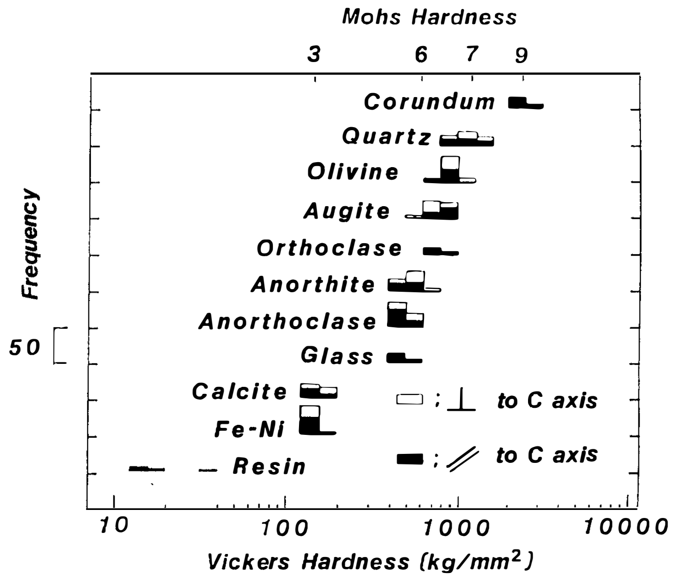

Fig. 4. Vickers hardness histograms of various types of terrestrial samples. Horizontal axis represents Vickers hardness (kg/mm²), and vertical axis represents frequency (one division is 50).

(actual magnification is about 2000) by using a digitizer (DT1000, GRAPHITEC Corp.). In order to obtain a range of variety in the hardness measurement, the same method was applied to terrestrial samples, including non-terrestrial Fe-Ni which was in Canyon Diablo, as shown in Fig. 4. The range of Vickers hardness is from 10 to 10000 kg/mm^2. In Fig. 4 the Mohs hardness is also indicated. Some samples might changes their hardness with crystal orientation, although our results from terrestrial samples indicate that their differences are very small. Since the actual diagonal lengths obtained were as small as about 10 microns, at least three points were measured to obtain a representative value of hardness for the whole metallic particle.

Using the personal-computer-aided image processing system (NAKANO *et al.*, 1988), we also analyzed the two-dimensional shape of metallic particles on polished sample surfaces, and calculated the fractal dimension, which is one of the indicators of shape irregularity (FUJII *et al.*, 1983). Fractal dimension of particles with cross sections greater than 0.001 mm^2 was calculated with the divider method (FUJII and NAKANO, 1988).

The Ni content of metallic particles was also analyzed by a scanning electron microscope (JEOL JSM-740) with energy dispersive X-ray microanalytical equipment (KEVEX DELTA CLASS III). Quantitative analyses were made with a focused beam of 15 kV accelerating voltage, and 1.5 nA beam current. Analyses were made at 3 to 10 points on each particle and averaged with the resultant accuracy of ± 0.1 wt% for Fe-Ni.

3. Results

Figure 5 shows a set of hardness histograms for metallic particles (Fe-Ni and troilite) in the eleven ordinary chondrites. Average values of Vickers hardness of

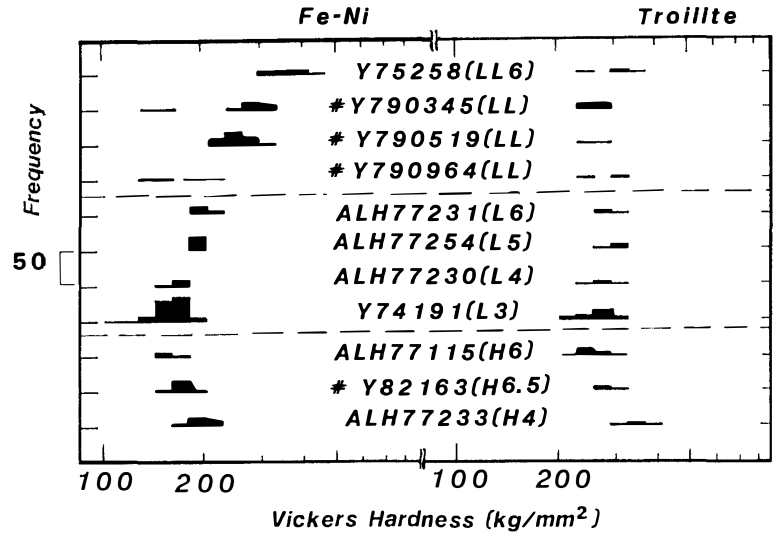

Fig. 5. Vickers hardness histograms for metallic particles in the ordinary chondrites. Horizontal axis represents Vickers hardness (kg/mm²), and vertical axis represents frequency (one division is 50).

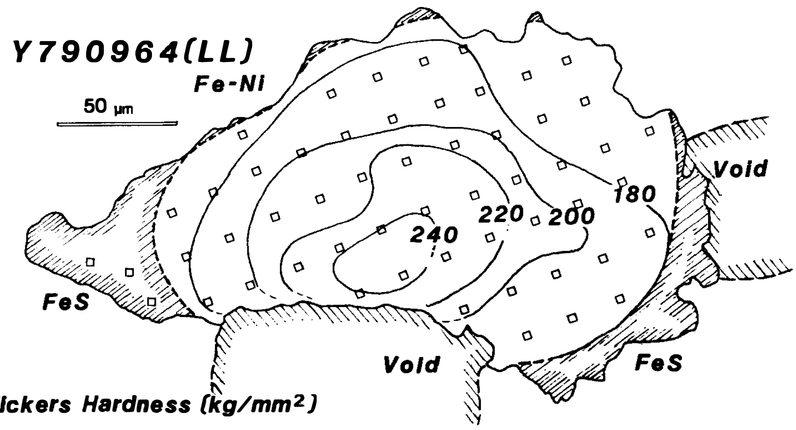

Fig. 6. 'Iso-hardness contour' map of Fe-Ni grain in Y-790964 (LL). Open squares indicate the measured points. Adjoining FeS and vesicles are also indicated.

taenite grains in Y-790964 (LL) and in Y-75258 (LL6) were 144 and 348 kg/mm², respectively. The result shows that when the amount of vesicles increases, the average hardness decreases. Average hardness values in unshocked L chondrites vary with petrologic types as observed by the values of the VFR (FUJII *et al.*, 1981) as follows: 160 kg/mm² in Y-74191 (L3), 169 kg/mm² in ALH-77230 (L3), 191 kg/mm² in ALH-77254 (L4), and 195 kg/mm² in ALH-77231 (L6).

Values of hardness might change within a single metallic particle: the hardness may be different near the grain boundary and near the core of the particle. Figure 6 shows the 'iso-hardness contour' map drawn by measuring as many as 51 points in one particle (taenite) with the cross section of 0.023 mm² in shock-melted Y-790964 (LL). The location of this taenite is shown as a circle with a short arrow in Fig. 1. The average hardness of this grain is 210±30 kg/mm². It is noted that this grain appears to be covered by troilite and adjacent to large voids, which may be indicative of vaporization and decomposition of FeS and subsequent loss of volatiles during shock heating (TAKEDA, 1988). Hardness near the grain boundary is lower than that near the core of the grain, though the difference is small relative to the variation among Fe-Ni particles in other chondrites. However, it could be an indication of shock effect because the shock deformation would concentrate at grain boundaries and periphery of vesicles.

Figure 7 shows the relation between Vickers hardness and Ni content in Fe-Ni grains. Most of grains in H and L chondrites are kamacites (Ni content of 4–7 wt%), and relatively large grains in LL chondrites are taenite (more than 15 wt%). Vickers

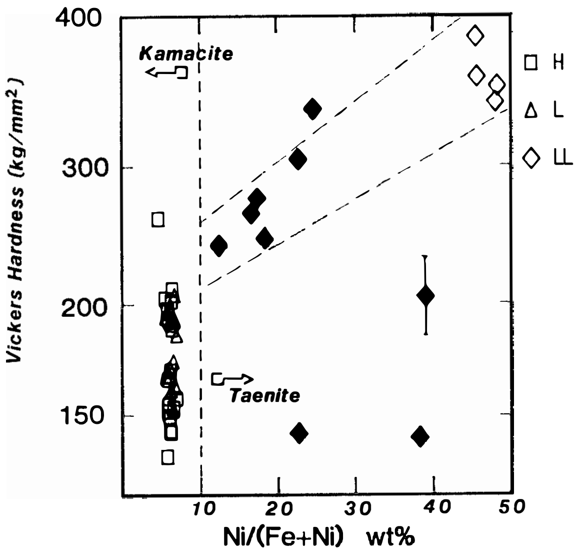

Fig. 7. Vickers hardness vs. Ni content in Fe-Ni grains. Horizontal axis represents Ni content (wt %), and vertical axis represent Vickers hardness (kg/mm²). Solid symbols represent shock-melted chondrites. A solid diamond with a vertical bar indicates the taenite grain in Fig. 6.

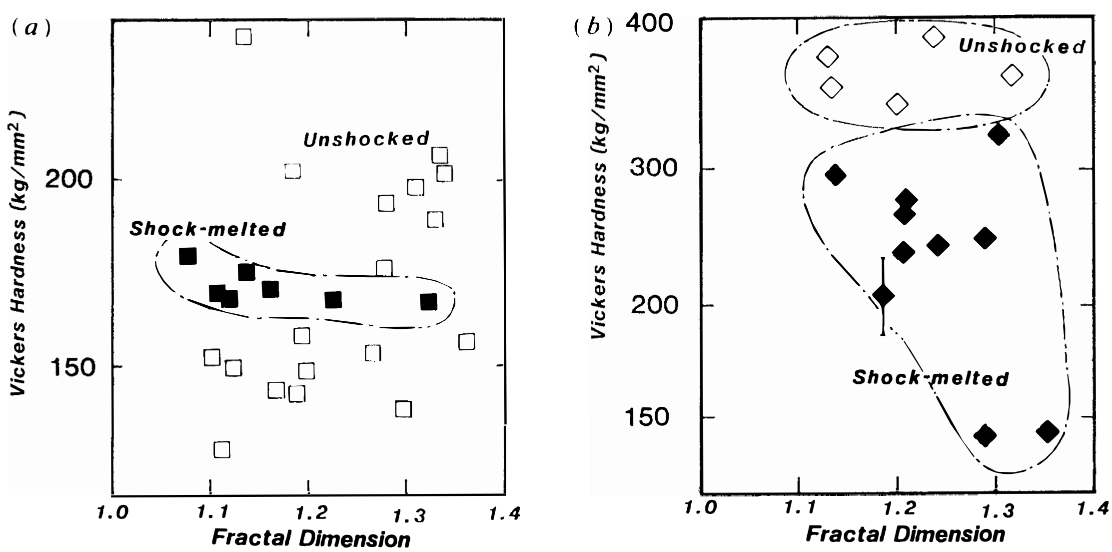

Fig. 8. Vickers hardness vs. fractal dimension of (a) H-type chondrites (all grains are kamacite) and (b) LL-type chondrites (all grains are taenites). Solid symbols represent shock-melted chondrites. A solid diamond with a vertical bar indicates the taenite grain in Figs. 6 and 7.

hardness values of taenite grains seem to increase with Ni content increase, although the number of grains measured is small and only one unshocked LL chondrite (Y-75258) shows high Ni content and large hardness values. In addition, it is not yet confirmed the presence of transformed γ-iron, which might be produced by shock-induced high pressures (SEARS *et al.*, 1984).

Figure 8 shows the relations between hardness and fractal dimension for H- and LL-type chondrites, respectively. It is noted that all grains in H chondrites (Fig. 8 (a)) are kamacite and those in LL chondrites (Fig. 8 (b)) are taenite. It seems likely that the larger values of fractal dimension (that means higher irregularity of grain shape) correspond to the lower hardness because shock effects were probably stronger.

If the shape of isolated metallic particles is controlled by the surface tension due

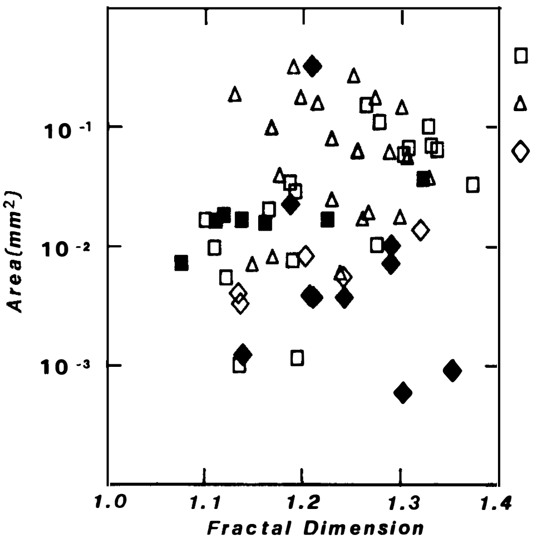

Fig. 9. Fractal dimension versus cross sectional area of Fe-Ni grains of chondrites. Solid symbols represent shock-melted chondrites.

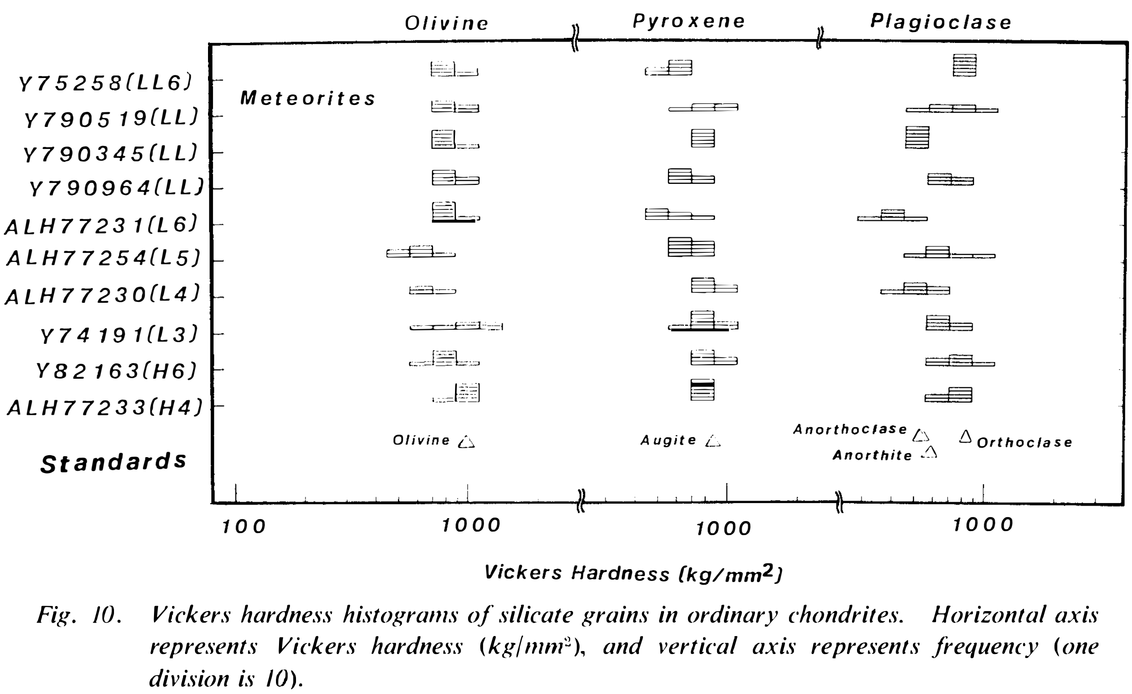

Fig. 10. Vickers hardness histograms of silicate grains in ordinary chondrites. Horizontal axis represents Vickers hardness (kg/mm²), and vertical axis represents frequency (one division is 10).

to large values relative to those of silicate minerals, the shape irregularity might change with its size independent of circumferential silicate grains and matrix. Figure 9, however, shows no such relation between fractal dimension and cross sectional area of Fe-Ni particles of ordinary chondrites. This suggests that the cooling rate was too fast to be effective for the isolated metallic particles to be deformed by surface tension, and the shape of such particles was affected by adjoining silicate minerals.

The Vickers hardnesses of silicate minerals were occassionally measured. Figure 10 shows histograms of the measured hardnesses for olivine, pyroxene, and plagioclase grains, but the data showed no systematic difference among minerals in unshocked and shock-melted chondrites.

4. Discussion and Conclusion

Figure 11 is a schematic diagram showing a probable trend of changes in the Vickers hardness and the fractal dimension. The irregular grains in shock-melted LL chondrites show lower hardness in comparison with those in unshocked LL chondrites. This might be explained that a shock wave was very effective for the isolated metallic particle of irregular surface (higher values of the fractal dimension), and the thermal annealing made its hardness lower, partly because metallic particles in LL chondrites are so scarcely distributed to be annealed efficiently and partly because the irregular shape is constrained by the grain boundaries of adjoining silicate minerals. This can be supported by another result: some taenite particles of high Ni content (shown in Fig. 7) which show anomalously low hardness, seem to keep their irregular shapes throughout the shock-melting event. In contract, it is apparent that kamacite particles in shock-melted H chondrites show uniform hardness compared to the wide variation of hardness in unshocked H chondrites. The large number of metallic particles and their relatively short distance distribution in H chondrites seem to affect such characteristics, although no clear explanation is made yet.

Shock compression is likely to cause an increase of dislocation density so that

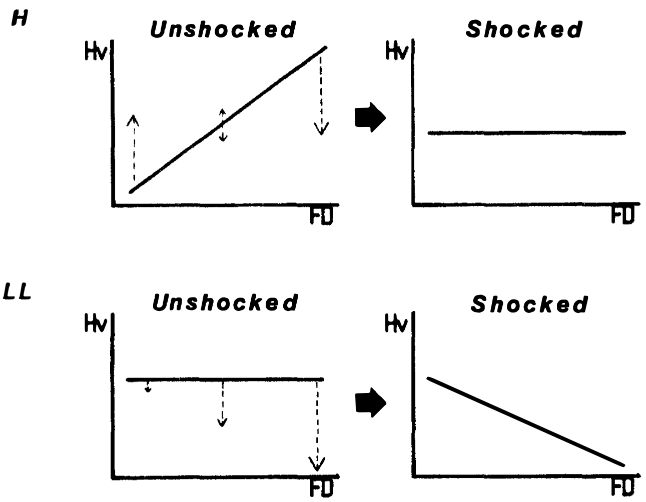

Fig. 11. Schematic diagram showing a probable trend of changes in fractal dimension with the Vickers hardness. For details see Fig. 8 and text.

one might expect the plastic hardening in metallic grains. However, our result turned out to be otherwise indicating a thermal annealing of Fe-Ni grains, although the annealing effects depend largely on cooling rates, the highest temperature, and/or heating duration in the samples. The residual bulk temperature for annealing in iron meteorite (Canyon Diablo) was estimated by BUCHWALD (1975) from its Vickers hardness of taenite, and the results were as follows: unshocked samples with lower temperature than 400°C show 170–210 kg/mm^2 of hardness, shock-annealed ones indicate 200–280 kg/mm^2, 160–200 kg/mm^2, 148–190 kg/mm^2, and 150–170 kg/mm^2, for temperatures about 500, >600, >750 and >900°C, respectively. Although the mechanical properties and Ni content of metallic grains in stony meteorites are different from those of iron meteorites, the same analogy for the effects of annealing might be useful for estimating the shock effects in ordinary chondrites.

If the large vesicles in shock-melted chondrites were produced by the shock-induced jetting nearby pre-existed pores (*e.g.*, KIEFFER, 1975) or by vaporization of FeS and subsequent loss of volatiles (TAKEDA, 1989), the weakening of metallic particles by thermal annealing could be more effective near the rim than the core of grain. As an example, the variation of hardness values in a single taenite particle in shock-melted LL chondrite (Y-790964) is shown in Fig. 6. The Ni content and the fractal dimension of this particle are indicated by a solid diamond with a vertical bar in Figs. 7 and 8(b). It seems likely for this particle that the hardness is severely lowered relative to the taenites with similar Ni content (Fig. 7), but the fractal dimension does not show any anomalous value among taenites (Fig. 8(b)). If this hardness distribution within a single taenite grain were produced by shock event, it would be unavoidable that the formation of adjacent large voids and the presence of FeS around this taenite grain should be closely related. It appeared to be concordant with the observations of shock effects in ureilites (*e.g.*, TAKEDA *et al.*, 1988) and cooling history (MIYAMOTO *et al.*, 1984).

Conclusions are as follows: (1) At present, however, we do not have reasonable explanations for shock effects on the hardness *vs.* shape irregularity relations, as some taenite grains show significantly reduced hardness presumably due to the thermal annealing effect. (2) Hardness variation within a single taenite grain indicates that the rim is more severely weakened than the core presumably due to the thermal annealing effects which are depending on cooling history and vaporization of FeS. (3) Shock effects are heterogeneous even on a microscopic scale. Irregular-shaped grains show shock effects more strongly. Further investigations are obviously needed to relate shock effects to dislocation density and texture.

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