ADHESIVE GROWTH AND ABRASION OF CHONDRULES DURING THE ACCRETION PROCESS

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Abstract: Droplet chondrules are classified into three groups based on the surface features. The group A chondrules, common in the equilibrated chondrites, do not have a clear boundary with the matrix. The ambiguity of the surfaces of group A can be explained by adhesion of the matrix materials coarsened during slow cooling. Chondrules in the unequilibrated chondrites belong to groups B and C. Though both groups B and C inherit spherical shapes of the melt droplets, the group B chondrules are characterized by zig-zag surfaces due to crystallization of olivine and pyroxene and/or adhesion of fine dusts. The group C chondrules have defined surfaces. Some of them are abraded by fine dusts into rounded shapes with smooth surfaces. The adhesion and abrasion of chondrules suggest that the accretion processes have occurred successively after the chondrule formation, and that the mechanical interaction between chondrules and dust during the accretion was different among the chemical groups and petrologic types of the chondrites.

1. Introduction

Chondrules have more or less rounded shapes and igneous textures. Those with spherical or spheroidal shapes and glassy or microcrystalline textures have been called "droplet" chondrules (KIEFFER, 1975). Others with irregular shapes and coarser texture have been called "clast" or "lithic" chondrules (DODD, 1981). The droplet chondrules are widely accepted to be quenched silicate melts. The clast chondrules may be fragments of larger rocks that experienced rubbing or abrasion processes (*e.g.* CHRISTOPHE MICHEL-LEVY, 1981; DODD, 1981).

The surface features of chondrules can provide some clues to the physical conditions which the chondrules experienced after solidification. GOODING and KEIL (1981) proposed three categories of chondrules with the specific surface features; a) the compound chondrules which attach or partially embed chondrule-like objects, b) the cratered chondrules which exhibit bowl-shaped depressions on their surfaces, and c) the rimmed chondrules which have distinctive shells or rinds. They considered that the compound and cratered chondrules have formed by collisions between the chondrules. However, only the limited number of chondrules show the surface features of their three distinct categories (GOODING and KEIL, 1981). For classification of many other chondrules, we need other categories, such as smoothness of surfaces.

The difference in shape between the chondrules of the unequilibrated chondrites

(UC's) and those of the equilibrated chondrites (EC's) has been generally ascribed to differences in thermal metamorphism after accretion (*e.g.* VAN SCHMUS and WOOD, 1967). However, WATANABE *et al.* (1985) have concluded that EC's have not experienced secondary thermal metamorphism. Therefore, the shape of the chondrules in the UC's and EC's should have been affected by the primary cooling process.

The cooling history of chondrules has been extensively studied based on the micro- and submicroscopic textures. However, only a few studies have been carried out on the mechanical conditions during the accretion to the parent bodies, except for the abrasion of lithic chondrules (CHRISTOPHE MICHEL-LEVY, 1981; DODD, 1981). In the present study, the change of the shapes of the droplet chondrules mechanically produced during the accretion process has been examined taking into account the surface features of chondrules. The droplet chondrules have been preferentially selected in this study, because their thermal history has been studied in detail, and because they inherit the spherical shape of the original silicate-melt droplets.

2. Result

Thin sections of the following chondrites are examined in the present study: Allende (CV3), Yamato-74191 (L3), Allan Hills-77015 (L3), ALH-77214 (L3), Y-75097 (L4), ALH-77230 (L4), Y-75102 (L5), Y-790957 (L5), Beaver (L5), Y-74077 (L6), Y-74190 (L6), Y-74362 (L6), Y-74454 (L6), Kyushu (L6), Gifu (L6), ALH-78084 (H3), Y-74155 (H4), Y-74371 (H5), Y-74647 (H5), ALH-77226 (H5), Jilin (H5), Takenouchi (H5), Y-74014 (H6), Y-74459 (H6), and Y-691 (E3).

The droplet chondrules can be divided into the following three groups, based on the surface morphology: group A for the chondrules with undefined surfaces, group B for the chondrules with rough surfaces, and group C for the chondrules with rounded, smooth and defined surfaces. Since the chondrules consist of many crystals of various sizes, it is difficult to define a parameter representing the surface roughness quantitatively as in the case of a continuous medium. However, the "rough" and "smooth" surfaces are defined in this paper as those with and without the zig-zag steps in the scale of the modal grain size of constituent grains in chondrules, respectively.

Group A: The chondrules in the EC's commonly belong to group A. Grains in the matrix of the EC's are as large as those in the chondrules, and the surfaces of the chondrules are not well defined. Figure 1a is a porphyritic olivine-pyroxene chondrule in the Jilin (H5) chondrite. The boundary between the chondrule and the matrix is ambiguous. The barred olivine chondrules and radial pyroxene chondrules (Figs. 1b and 1c) are also irregular in shape with no clear boundary with the matrix.

Group B: The group B chondrules are abundant in the UC's and the petrologic type 4 chondrites. Especially in the Allende meteorite (CV3), almost all chondrules belong to group B.

Figures 2a–2d show the porphyritic olivine-pyroxene chondrules in the ALH-77214 (L3) chondrite. All of them have glass or fine-grained mesostasis and are nearly spherical in shape, indicating molten or partially molten stage. However, they have finely zig-zagged surfaces determined by the morphology of the constituent crystals. In Figs. 2b and 2d, euhedral pyroxene and olivine crystals protrude from the surfaces

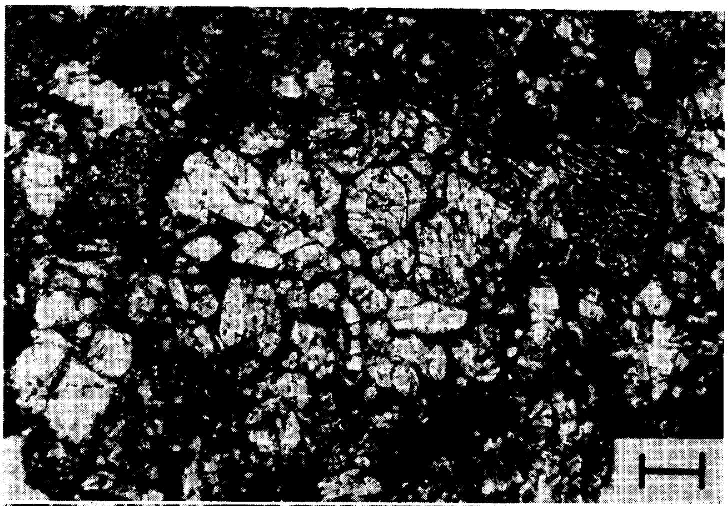


Fig. 1a. Porphyritic olivine-pyroxene chondrule in Jilin (H5). Note the ambiguity of the boundary between the chondrule and the matrix, which is relatively coarse grained. Scale bar, 0.2 mm. Transmitted, plane polarized light.

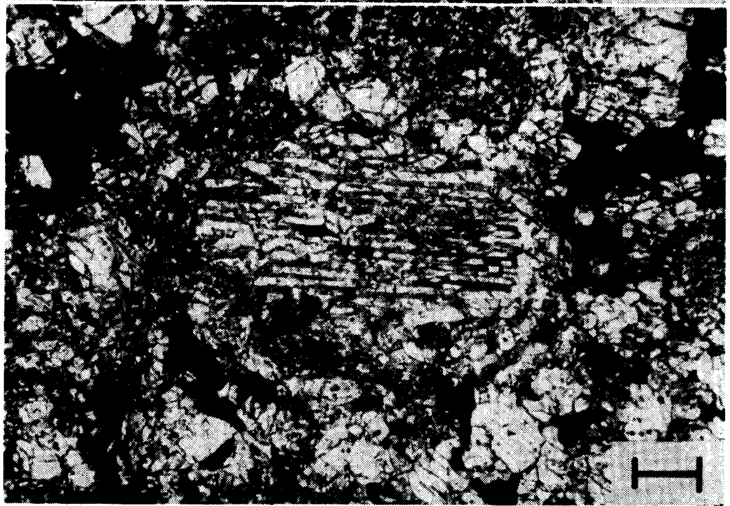


Fig. 1b. Barred olivine chondrule in Y-75102 (L6). The surface of the chondrule is poorly defined. Scale bar, 0.2 mm. Transmitted, plane polarized light.

Fig. 1c. Radial pyroxene chondrule in Beaver (L5). The chondrule is not really spherical, and the surface not smooth but rugged. Scale bar, 0.2 mm. Transmitted, plane polarized light.

of the chondrules, respectively, resulting in some variation of the smoothness of the surfaces.

The barred olivine chondrules (Figs. 2e–2g) consist of a few sets of olivine bars and glass, shelled by olivine in the same crystallographic orientation with one set of the

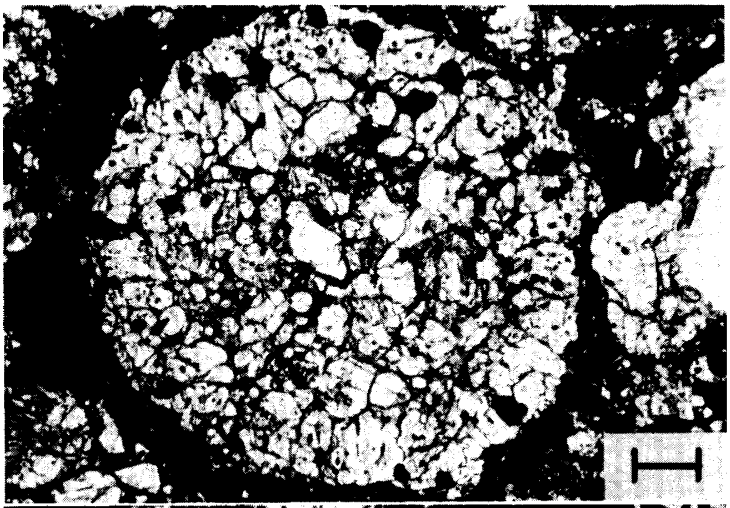


Fig. 2a. Porphyritic olivine-pyroxene chondrule in ALH-77214 (L3). The chondrule has a zig-zag surface. The internal texture is similar to Fig. 3a. Scale bar, 0.2 mm. Transmitted, plane polarized light.

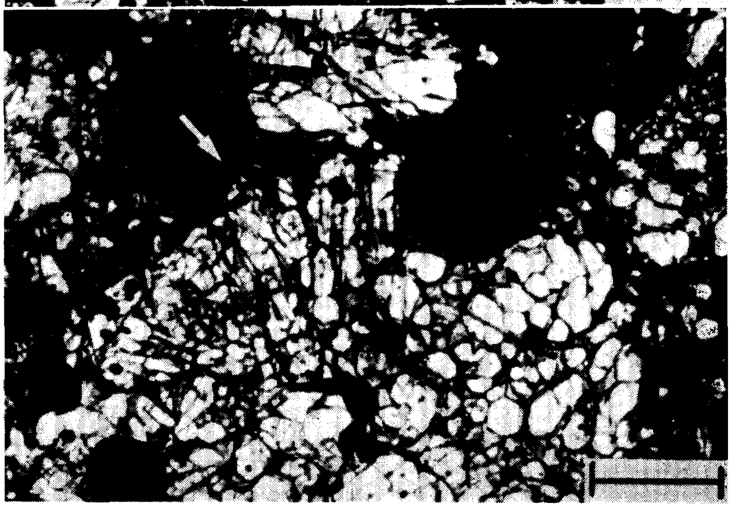


Fig. 2b. Irregularly shaped porphyritic olivine-pyroxene chondrule in ALH-77214 (L3). Euhedral pyroxene grains protrude from the surface of the chondrule as indicated by an arrow. Scale bar, 0.2 mm. Transmitted, plane polarized light.

olivine bars. The olivine crystals in the shell are subhedral and sometimes show overall spherical shapes. The surfaces of the barred olivine chondrules of group B are not smooth but rough.

The composite chondrules of group B are often observed. The barred olivine chondrule in Allende (Fig. 2g) shows the adhesion of two small barred olivine chondrules. The composite chondrule consisting of the barred olivine chondrule surrounded by the pyroxene chondrule is also found in Y-74191 (L3) (Fig. 2h).

Some of the group B chondrules are surrounded by fine grains, so as to cause quite an irregular surface. Especially in the Allende meteorite, this character is commonly observed. Dark-zoned chondrules (DODD and VAN SCHMUS, 1971) are also considered to belong to this group.

Group C: The group C chondrules with rounded and distinct surfaces are observed mainly in the chondrites of the UC's.

A porphyritic olivine-pyroxene chondrule (Fig. 3a) has a similar internal texture to, but quite a different round and smooth surface (Fig. 3b) from that of group B in Fig. 2a. In Fig. 3c, large pyroxene crystals are euhedral inside the chondrule, but are cut by curved and smooth surface of the chondrule. Figure 3d is a back-scattered electron image near the surface of a porphyritic olivine-pyroxene chondrule. The

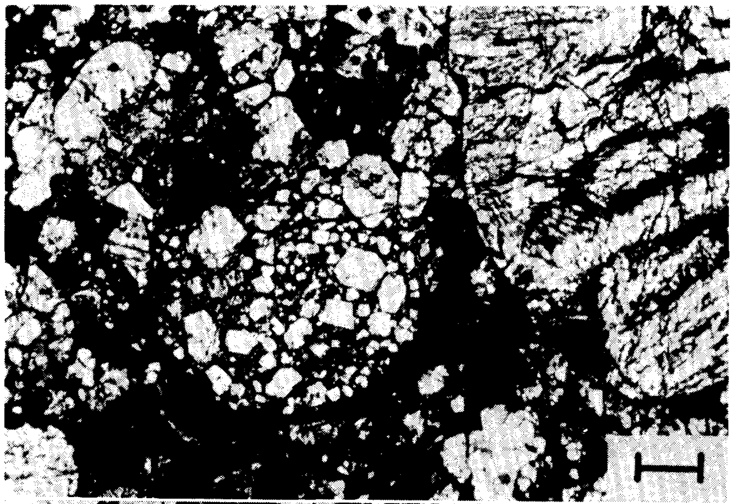


Fig. 2c. Porphyritic olivine-pyroxene chondrule in ALH-77214 (L3). Crystals are euhedral inside the chondrule and even at the rim. Scale bar, 0.2 mm. Transmitted, plane polarized light.

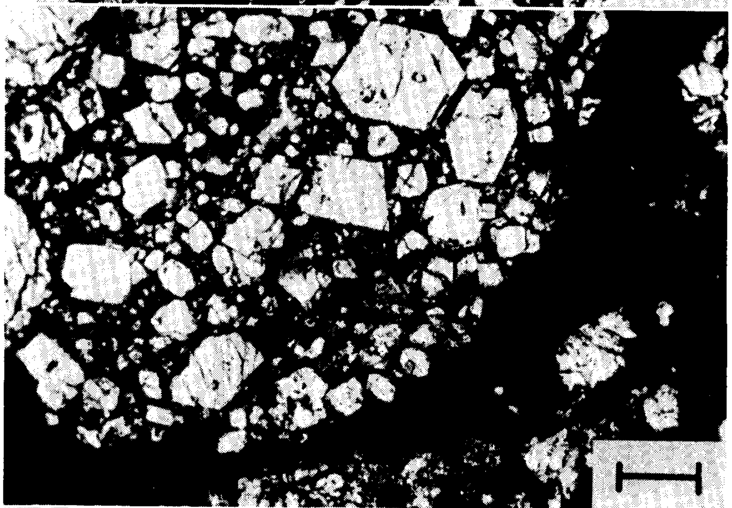


Fig. 2d. Enlarged micrograph of chondrule in Fig. 2c. Olivine crystals at the surface of the chondrule are euhedral, giving a zig-zag shape of the chondrule. Scale bar, 0.1 mm. Transmitted, plane polarized light.

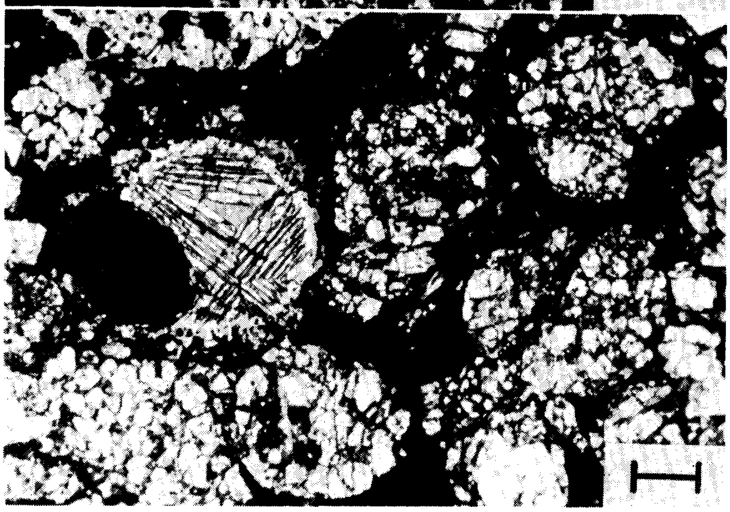


Fig. 2e. Barred olivine chondrule in ALH-77214 (L3). Chondrule consists of large and small metal grains, olivine bars, glass and olivine shell. The surface is not smooth and fine grains are observed on it. Scale bar, 0.2 mm. Transmitted, plane polarized light.

compositional zoning of pyroxene with Ca-poor core in dark contrast and Ca-rich rim in bright contrast is cut by round surface of the chondrule.

A more typical example of group C is the pyroxene single crystal chondrule with a round and clear surface boundary (Fig. 3e). This consists of orthopyroxene with pigeonite rim and groundmass at the only one end. Partially melted zones exist in

Fig. 2f. Barred olivine chondrule in ALH-77214 (L3). Olivine crystal coats half of the rim of the chondrule. While the chondrule is almost spherical, the surface is not smooth but zig-zag. Scale bar, 0.2 mm. Transmitted, plane polarized light.

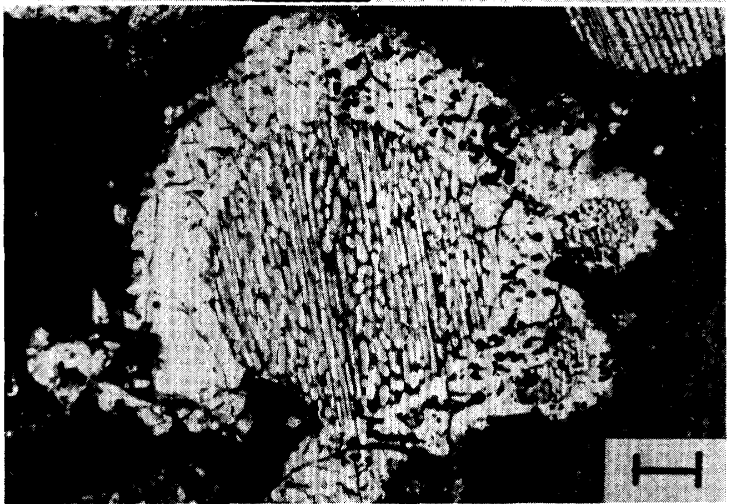


Fig. 2g. Composite barred olivine chondrule in Allende (CV3). Two small barred olivine chondrules adhere to a large one. Scale bar, 0.2 mm. Transmitted, plane polarized light.

Fig. 2h. Composite chondrule in Y-74191 (L3). A barred olivine chondrule inside, and crystals of porphyritic olivine-pyroxene outside. Scale bar, 0.2 mm. Transmitted, plane polarized light.

the orthopyroxene along its *c*-axis.

Another example of group C is a barred olivine chondrule in Fig. 3f. This chondrule consists of olivine laths and glass, which form round and clear surface boundaries of the chondrule without the olivine shell as in group B (Figs. 2e–2g). The barred olivine chondrule in Fig. 3g has a shell with not rough but smooth surfaces.

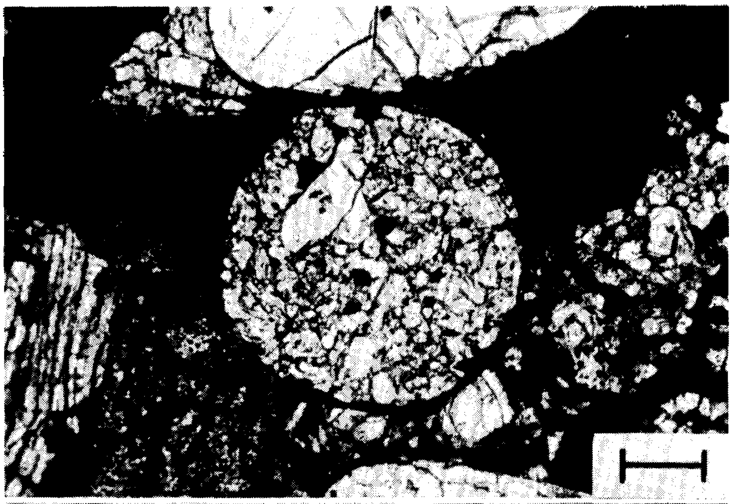


Fig. 3a. Porphyritic olivine-pyroxene chondrule in ALH-77214 (L3) with a rounded shape. Scale bar, 0.1 mm. Transmitted, plane polarized light.

Fig. 3b. Enlarged micrograph of the chondrule in (Fig. 3a). Grains at the surface of the chondrule are not euhedral but cut in rounded shapes as indicated by an arrow. Compare with the zig-zag surfaced chondrule in Fig. 2d. Scale bar, 0.1 mm. Transmitted, crossed nicols.

Fig. 3c. Spherical porphyritic olivine-pyroxene chondrule in ALH-78084 (H3). Large orthopyroxene grains are cut with rounded and clear surfaces at the right and bottom wall of the chondrule. Scale bar, 0.1 mm. Transmitted, plane polarized light.

The radial pyroxene chondrules commonly show very smooth surfaces (Fig. 3h). Figure 3i is a composite chondrule consisting of a radial pyroxene chondrule shelled by microporphyries of olivine and pyroxene. The shape is nearly hemispherical, but the surface is smooth.

The Y-691 (E3) chondrite has a fragmentary texture (Figs. 4a and 4b). However,

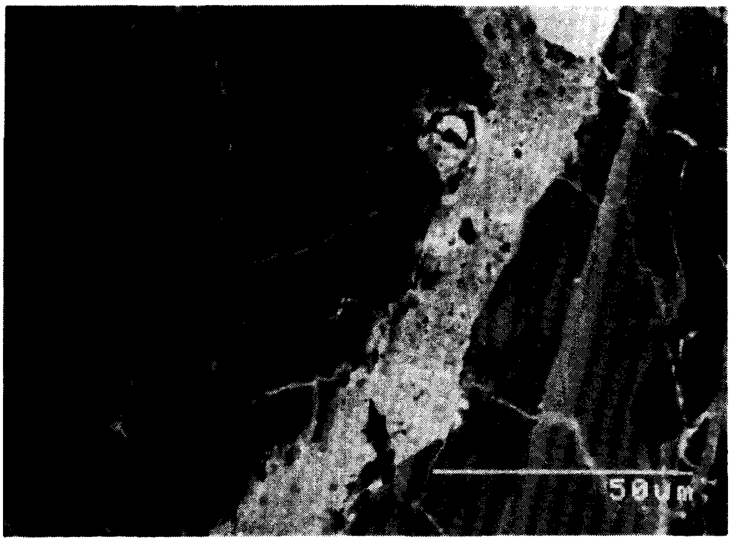


Fig. 3d. Back-scattered electron image of a porphyritic olivine pyroxene chondrule in ALH-77214 (L3). Compositional zoning of pyroxene (with rim in bright contrast) is cut by the rounded surface of the chondrule, as indicated by an arrow.

these broken chondrules show the characteristics of group C, that is, smooth surfaces and round angles.

Relative abundances: Figure 5 shows the relative abundances of the groups A, B, and C chondrules among 45 chondrules in ALH-78084 (H3), 68 in ALH-77214 (L3), 19 in ALH-77230 (L4) and 50 in Beaver (L5). UC's of H and L groups include the group B and C chondrules, while EC's consist only of group A. Most of the chondrules in Y-691 (E3) were broken but show the characteristics of group C.

3. Discussion

3.1. Surface features of chondrules

Since EC's have not experienced significant secondary thermal metamorphism through which the morphology of chondrules changed, the petrologic types of the chondrites are considered to be due to the cooling rate during or before the accretion (WATANABE *et al*., 1985). Therefore, because the group A chondrules are found in the EC's (Fig. 5), they must have cooled with slower rates than groups B and C in the UC's. Slow cooling rates of the group A chondrules changed the initial spherical shapes of the melts to irregular ones by the crystal growth within the chondrules. Moreover, the group A chondrules show the adhesion of the coarse materials, which effectively obscures the boundary between chondrules and matrices.

The groups B and C chondrules are common in the UC's (Fig. 5) and thus cooled more rapidly than the group A chondrules. Both chondrules basically inherit the spherical shapes of melt droplet.

The porphyritic chondrules of group B have the euhedral crystals even at the surfaces, resulting in the zig-zag surfaces of chondrules (Figs. 2b and 2d). CHRISTOPHE MICHEL-LEVY (1981) suggested that the slowly cooled droplets have crystals projecting over the curved surfaces. It is also possible that euhedral grains in the surfaces of some of the group B chondrules result from preferential lacking of the mesostasis such as glass by abrasion. On the other hand, some of the group B chondrules, such as dark rimmed chondrules, were adhered to by fine dusts (*e.g.* ASHWORTH, 1977).

Fig. 3e. Spherical pyroxene chondrule in ALH-77015 (L3). It consists of an orthopyroxene single crystal with pigeonite rim and mesostasis only on the right side of the chondrule. Scale bar, 0.2 mm. Transmitted, plane polarized light.

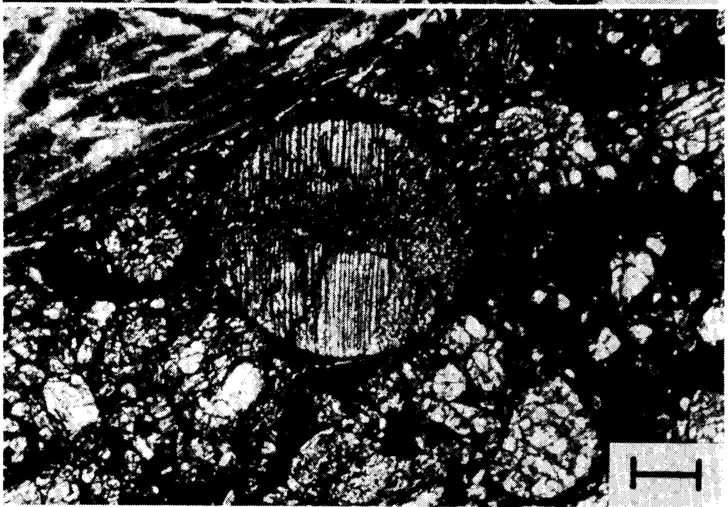


Fig. 3f. Barred olivine chondrule in ALH-77015 (L3). Note the smooth surface without shelling olivine. Scale bar, 0.2 mm. Transmitted, plane polarized light.

Fig. 3g. Barred olivine chondrule in Y-74191 (L3). The surface of the olivine shell is rounded and smooth. Scale bar, 0.2 mm. Transmitted, plane polarized light.

As an origin of the chondrules of group C, it has been considered that the spherical shape and smooth surface simply inherit those of the silicate-droplets, with crystals being frozen in glass (CHRISTOPHE MICHEL-LEVY, 1981). In fact, radial pyroxene chondrules (*e.g.* Fig. 3h) of group C in the spherical shape with smooth surface do not show any definitive evidence of modification other than the quenched

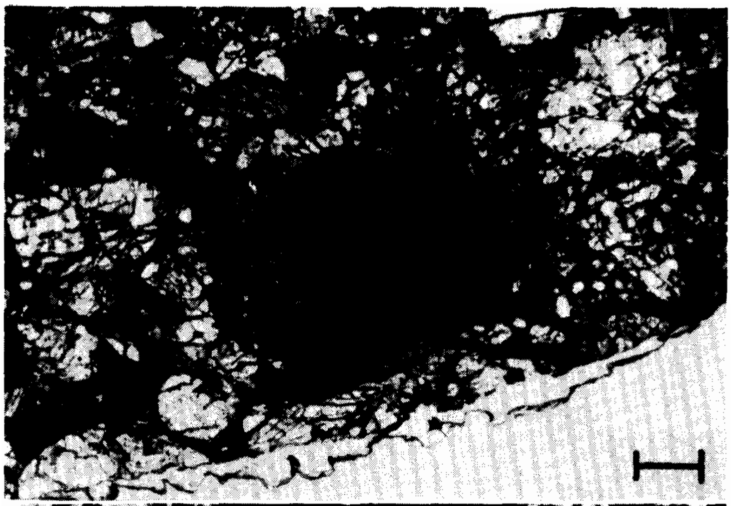


Fig. 3h. Radial pyroxene chondrule composed of very narrow pyroxene fibers in ALH-77015 (L3). The surface of the chondrule is smooth and clear. Scale bar, 0.2 mm. Transmitted, plane polarized light.

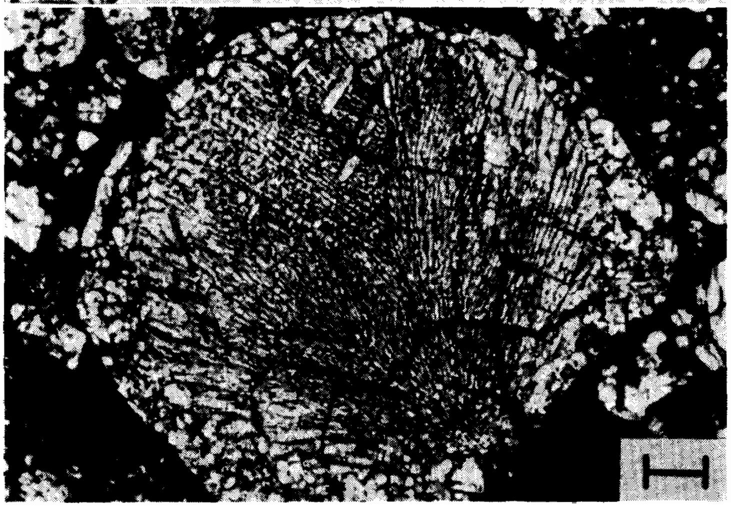


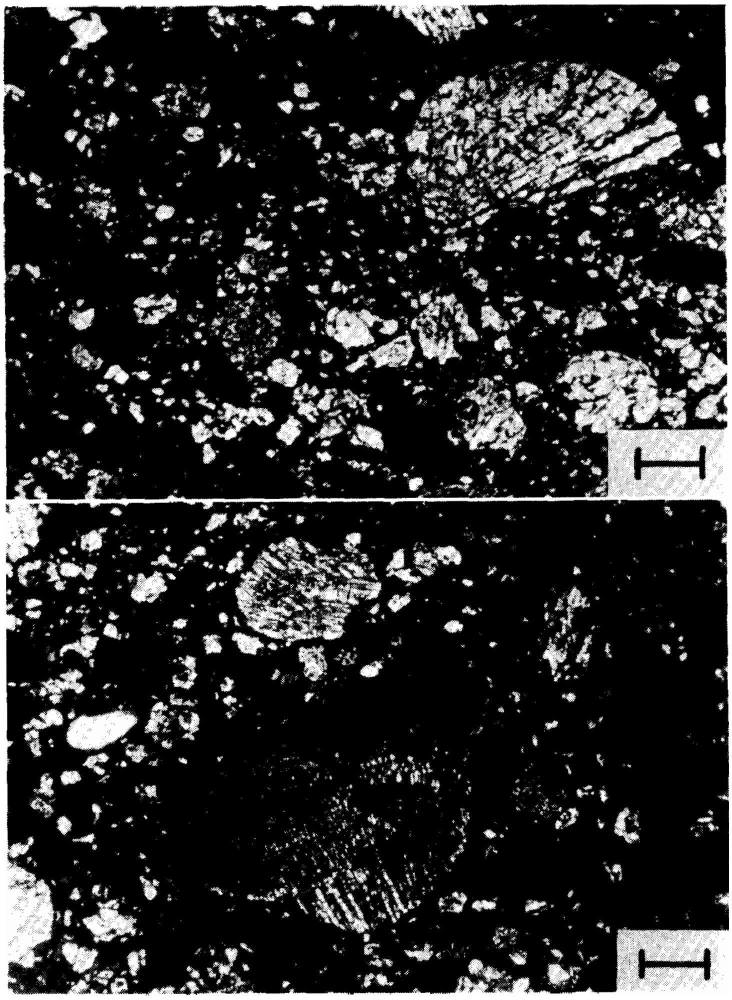
Fig. 3i. Composite chondrule in ALH-77214 (L3). A radial pyroxene inside, and porphyritic olivine-pyroxene outside. The outermost surface is smooth. Scale bar, 0.2 mm. Transmitted, plane polarized light.

droplets. However, some chondrules of group C show an additional modification of chondrules, which is clarified by comparing the surface morphology between groups B and C. The back-scattered electron image of a group C chondrule (Fig. 3d) shows that the compositional zoning of pyroxene is cut by the rounded surface of the chondrule. It suggests that the smooth and curved shapes of crystals of this chondrule must have been modified by abrasion from the zig-zag shapes as in group B.

The other typical example of the abraded chondrule is the chondrule of a single pyroxene crystal and the mesostasis only on oneside (Fig. 3e), which must have changed in shape by abrasion from an euhedral crystal.

The barred olivine chondrules commonly consist of the olivine laths and glass shelled by irregular olivine shells as those of group B (Figs. 2e–2g). However, the typical group C barred olivine chondrule (Fig. 3f) does not have the shell. From a viewpoint of the abrasion, this difference can be explained by assuming that the chondrule in Fig. 3f had a shell during crystallization which was later abraded.

In conclusion, the abrasion occurred not only in the lithic chondrules (*e.g.* CHRISTOPHE MICHEL-LEVY, 1981; DODD, 1981), but also in some of the droplet chondrules.



Figs. 4a and 4b. Thin section of Y-691 (E3), showing extensive destruction and fragmentation of particles. Scale bar, 0.2 mm. Transmitted, plane polarized light.

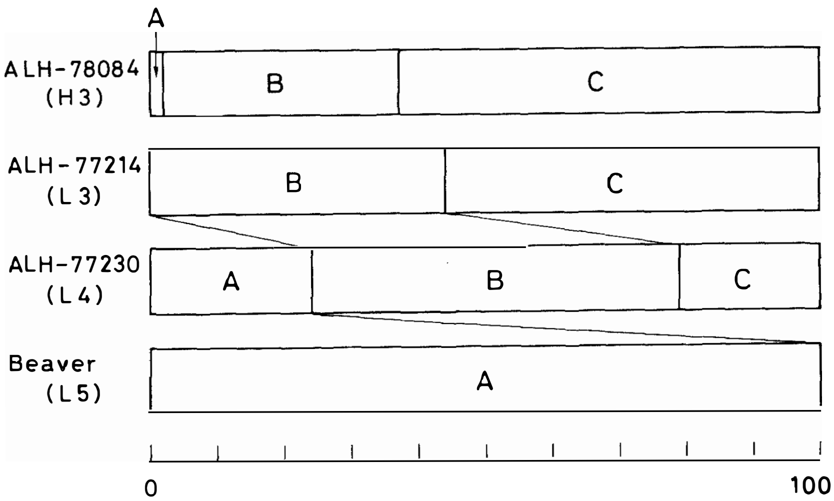


Fig. 5. Relative abundance of the groups A, B and C chondrules in the ALH-78084 (H3), ALH-77214 (L3), ALH-77230 (L4) and Beaver (L5) chondrites.

3.2. Adhesive growth and abrasion of chondrules

The adhesion must have occurred in collision between partially molten chondrules and solid dusts, when the chondrules glued the dusts on their wet surfaces. The abrasion of the group C chondrules must have occurred in collision between the chondrules with solidified surfaces and the abradants. When the abradants were large particles such as chondrules and lithic fragments, breaking of the chondrule as in Y-691 should have occurred. Therefore, in order for the abrasion to occur, the mass and relative speed of the abradant must be in some limited values. Because the group C chondrules are commonly surrounded by fine-grained matrix region of about several tens μm in width, most probable abradant must be these fine grains.

3.3. Accretion process

The micro- and submicroscopic textures of chondrules indicate that the chondrules cooled not in vacuum, but in some surrounding media (TSUCHIYAMA *et al.*, 1980; KITAMURA *et al.*, 1983). The adhesion and abrasion of chondrules require dusts which have surrounded the chondrules. The adhesion requires partially molten chondrules. Therefore, the accretion must have occurred successively after the formation of chondrules under different mechanical conditions among the petrologic types.

Different proportions of the group B to C chondrules among the chemical groups of the UC's also indicate different mechanical conditions during the accretion. The formation process of carbonaceous chondrites must be discussed separately from that of ordinary chondrites (*e.g.* DODD, 1981). However, since the abrasion of chondrules works only on dry surfaces, or after solidification of chondrules, mechanical conditions during accretion of chondrules can be discussed for carbonaceous as well as for other unequilibrated chondrites based on the abundance of the abraded chondrules. Because the cooling rates of chondrules estimated by the decomposition texture of pyroxenes in Y-74191 (L3) and Allende (CV3) are of the same order (KITAMURA *et al.*, 1983, 1984), the different relative abundance of groups B and C between L3 and Allende does reflect their different mechanical conditions, and the Allende chondrite with a small amount of the group C chondrules should have accreted more statically than the L3 chondrite. On the other hand, because breaking and fragmentation are intensive in Y-691 (E3), the accretion of E3 must have been more violent than that of the other chemical groups.

4. Concluding Remarks

(1) The droplet chondrules can be classified into three groups based on the characteristics of the surfaces. The group A chondrules, common in the EC's, show no clear boundaries with the matrix. They suffered slow cooling during which the coarsened matrix materials adhered onto the surfaces of the chondrules.

The group B chondrules, common in the UC's especially in Allende (CV3), basically keep the spherical shapes of melt droplet, but give zig-zag steps of surfaces due to the euhedral shapes of olivine and pyroxene in the chondrules and/or adhesion of the dusts.

The group C chondrules, also common in the UC's, show characteristically round surfaces, some of which inherited droplet shapes, but others were smoothed by the abrasion processes after solidification during the rapid cooling.

(2) The abrasion of and adhesion on the surfaces of chondrules occurred in the accretion process. This fact requires that the accretion occurred successively after the chondrule formation.

(3) The mechanical conditions during the accretion were also different among the chemical groups of the UC's. The Allende meteorite has accreted more statically than the L3 chondrites. The accretion of Y-691 (E3) was more violent than the other UC's.

Acknowledgments

The authors thank Prof. N. MORIMOTO, Dr. A. TSUCHIYAMA and Mr. H. ISOBE of Kyoto University for their valuable discussions and critical reading of the manuscript. Thanks are also due to Prof. T. NAGATA and Dr. K. YANAI of the National Institute of Polar Research, and Prof. S. BANNO of Kyoto University for providing us with the Antarctic meteorites and Japanese meteorites, respectively.

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(Received August 5, 1985; Revised manuscript received December 5, 1985)