EFFECTS OF PRECOOLING THERMAL HISTORY AND COOLING RATE ON THE TEXTURE OF CHONDRULES: A PRELIMINARY REPORT

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***Abstract*:** Effect of precooling thermal history of chondrules on the textures of chondrules was examined by crystallizing melts of chondrule compositions with or without relict crystals at cooling rates of about 50°C/min. Textures formed from super-liquidus temperatures (radial or barred olivine texture) were strikingly different from those formed from sub-liquidus temperatures (porphyritic or microporphyritic texture). Effect of cooling rate was also examined with cooling rates ranging from 500 to 5.3°C/hr. The cooling rate for producing radial or barred pyroxene texture ranges from about 200 to less than 5°C/hr, whereas radial or barred olivine texture was produced with cooling rates greater than about 100°C/hr.

1. Introduction

Many experimental works have been done on reproducing textures of chondrules in order to estimate conditions of chondrule formation (NELSON *et al.*, 1972; BLANDER *et al.*, 1976; TSUCHIYAMA *et al.*, 1980; HEWINS *et al.*, 1981); for example, cooling rate of barred olivine chondrules was estimated to be about 100°C/min (TSUCHIYAMA *et al.*, 1980). However, conditions of formation of porphyritic texture which is most popularly observed in chondrules, are not well known, and differences in conditions of formation between radial pyroxene and radial olivine chondrule are unknown (TSUCHIYAMA *et al.*, 1980).

It has been pointed out that texture is strongly affected by nucleation kinetics and thermal history such as cooling rate (*e.g.*, LOFGREN, 1980). In our experimental study, in order to distinguish and clarify these effects, two types of experiments were conducted. Here, preliminary results are reported and promising clues to the above problems will be presented.

2. Experiments

Finely powdered starting materials of two chondrule compositions were used; sample 1 is a mixture of olivine, pyroxene and albite (SiO_2=43.6%, FeO=18.5% and MgO=29.6%), and sample 2 is Yamato-74115 chondrite from which metallic iron was removed (SiO_2=53.5%, FeO=12.1% and MgO=22.1%). The size of each crystal in the starting materials ranges from less than 1 μm to a few μm. Experimental technique was the same as the previous experiments (TSUCHIYAMA *et al.*, 1980); Pt-wire loop method was applied and P_{O_2} varied from about 10^{-9} atm (1600°C) to 10^{-12} atm (1200°C).

Two thermal procedures were adopted; (i) after the charges were heated at various temperatures (super- or sub-liquidus conditions) for 2 min, they were cooled with non-linear cooling rate (from 80°C/min at 1600°C to 20°C/min at 1200°C) to examine nucleation kinetics, and (ii) after the charges were completely melted at 1485°C for 2 min, they were cooled with constant cooling rate ranging from 500 to 5.3 °C/hr to examine the effect of cooling rate (only for sample 2). In both the experiments, the changes were quenched in water at 1200°C. In connection with the experiment (i), the charges were quenched immediately after heating in order to examine presence or absence of crystalline precursors before cooling.

3. Results and Discussion

3.1. Effect of precooling history on texture

Figs. 1, 2, 3 and 4 show textures of the charges cooled at 80–20°C/min or by immediate quenching from different temperatures. For sample 1, olivine is an only crystalline phase. For sample 2, all crystalline charges contain olivine, and pyroxene also crystallizes in the charges melted at temperatures lower than about 1400°C. All the charges have residual glass.

Judging from the results of the quenching experiments, liquidus temperatures of olivine are considered to be about 1580°C and 1440°C for samples 1 and 2, respectively. However, it should be noted that the liquidus temperatures cannot be determined precisely because the run duration of the quenching experiments is only 2 min. When the charges are cooled from completely melted state, crystals nucleate probably at high degree of supercoolings and as a result radial and/or barred olivine crystals are formed (Figs. 1a and 3a–f). On cooling from much higher temperature than the liquidus, no crystal nucleates and glassy phase is formed for sample 2 (melting temperature is higher than 1560°C). On the other hand, when the charges are cooled from partially melted state (*i.e.*, sub-liquidus temperature) with crystalline precursors (Figs. 2c–f and 4d–f), porphyritic to microporphyritic texture with equant olivine and/or pyroxene crystals is formed (Figs. 1d–j and 3i–l). With decreasing temperature of heating, the size of the equant crystals becomes smaller from a few hundreds to a few μm (Figs. 1d–i and 3i–l). On cooling from near-liquidus temperature, quench crystals are found in quenching experiments (Figs. 2a, b and 4a–c) so that it is hard to make sure of presence or absence of crystalline precursors. However, textures of these charges are different from those cooled from super-liquidus temperatures and those from sub-liquidus temperatures; coarse barred olivine crystals are formed for sample 1 (Figs. 1b, c) and acicular olivine crystals are formed for sample 2 (Figs. 3g, h).

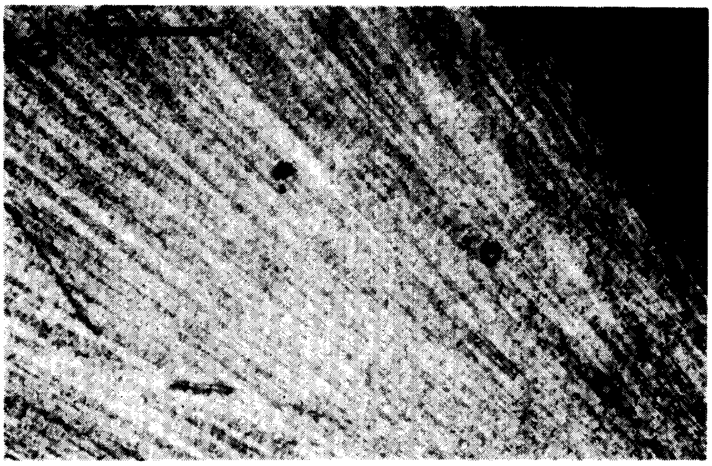

Fig. 1a. Run 514, cooled from 1598°C. Radial olivine texture.

Fig. 1b. Run 541, cooled from 1589°C. Coarse barred olivine texture.

Fig. 1c. Run 544, cooled from 1580°C. Coarse barred olivine texture.

Figs. 1a–j. Photomicrographs of thin sections of charges cooled at 80–20°C/min from different temperatures of heating on sample 1. Scale bars, except in Fig. 1j, are 0.2 mm; scale bar for Fig. 1j is 0.1 mm.

Fig. 1d. Run 506, cooled from 1568°C. Porphyritic olivine texture.

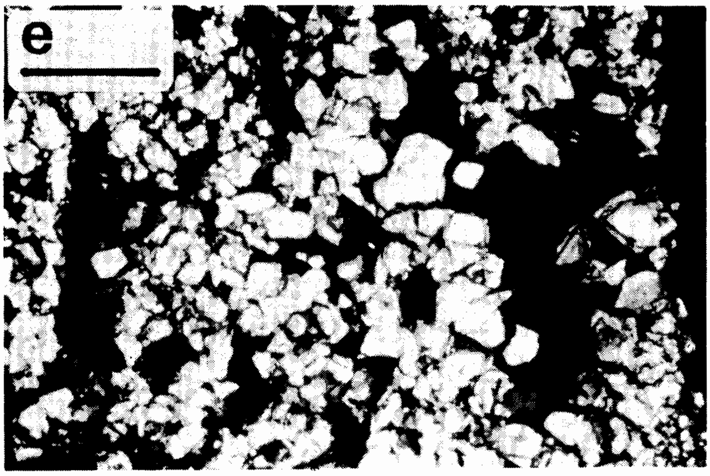

Fig. 1e. Run 508, cooled from 1549°C. Porphyritic olivine texture.

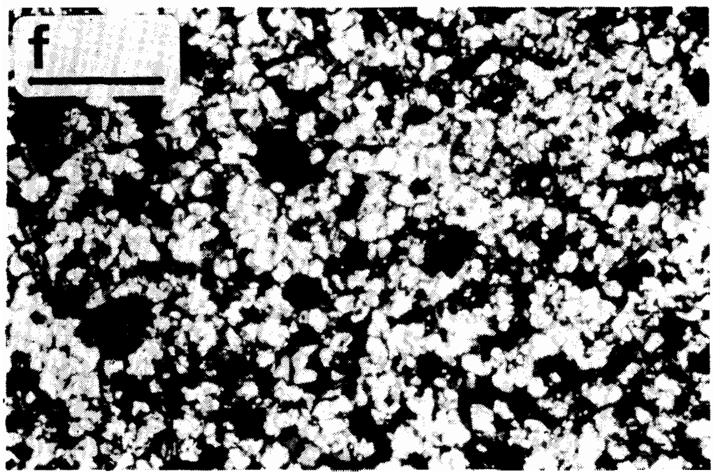

Fig. 1f. Run 526, cooled from 1529°C. Porphyritic olivine texture.

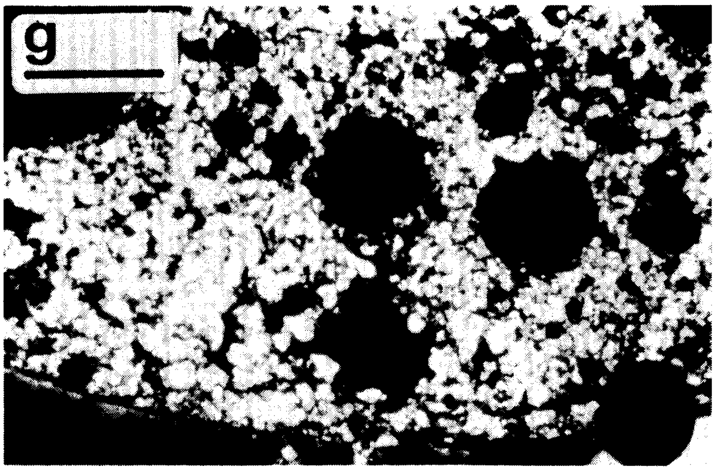

Fig. 1g. Run 538, cooled from 1512°C. Porphyritic olivine texture.

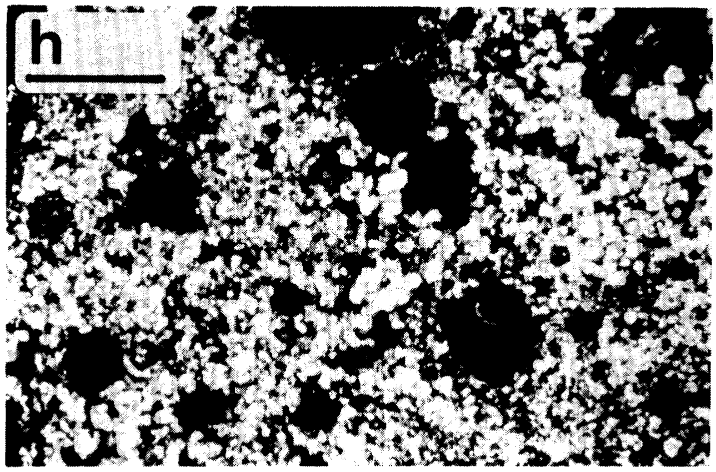

Fig. 1h. Run 523, cooled from 1491°C. Porphyritic olivine texture.

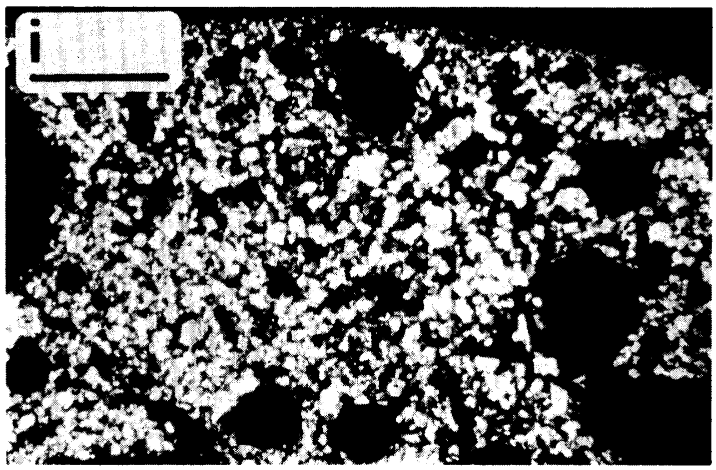

Fig. 1i. Run 518, cooled from 1451°C. Porphyritic olivine texture.

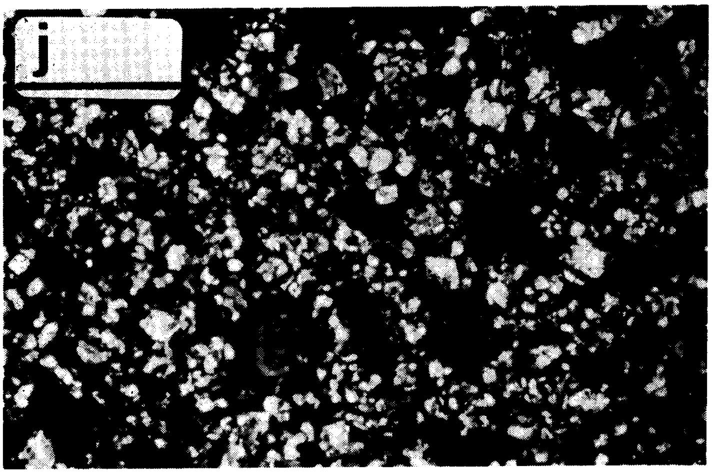

Fig. 1j. Close-up of Fig. 1i.

Fig. 2a. Run 540, quenched from 1589°C. Quench crystals are present.

Fig. 2b. Run 543, quenched from 1580°C. Quench crystals are present.

Figs. 2a–h. Photomicrographs of thin sections of charges quenched from different temperatures of heating on sample 1. Scales bars are 0.2 mm.

Fig. 2c. *Run 505, quenched from 1568°C. Relict olivine rimmed by quench crystals is present.*

Fig. 2d. *Run 507, quenched from 1549°C. Relict olivine rimmed by quench crystals is present.*

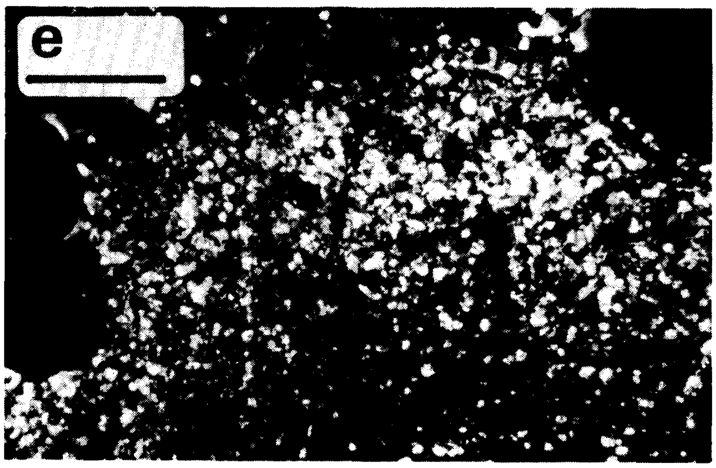

Fig. 2e. *Run 537, quenched from 1512°C. Relict olivine is present.*

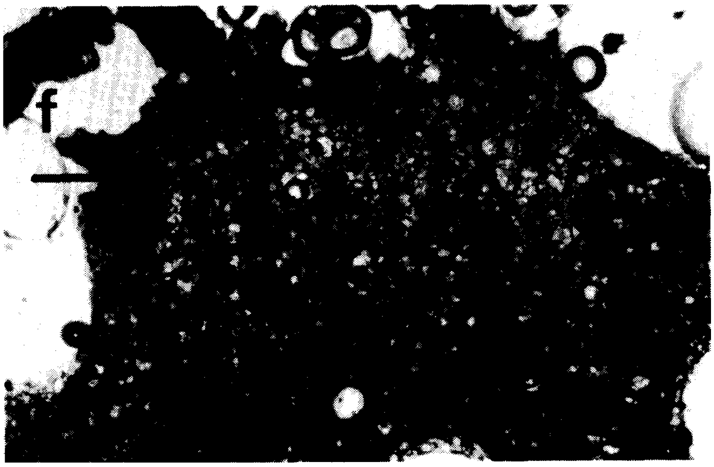

Fig. 2f. *Same as Fig. 2e. Open nichol.*

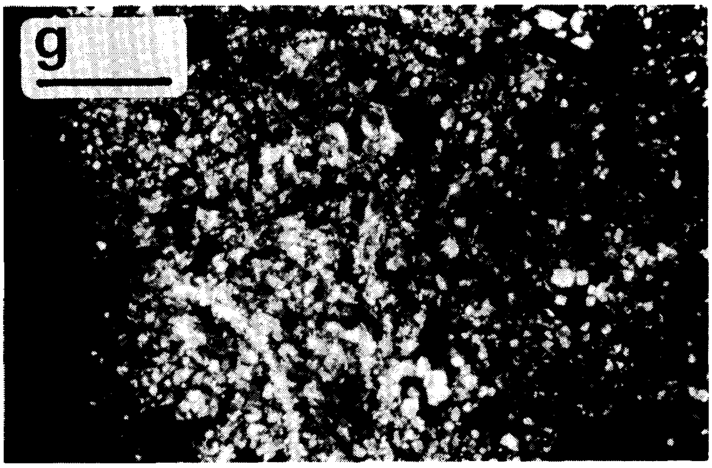

Fig. 2g. *Run 522, quenched from 1491°C. Relict olivine is present.*

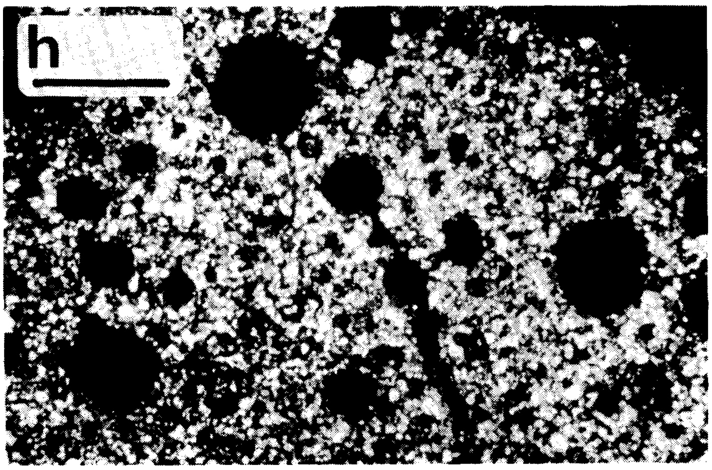

Fig. 2h. *Run 516, quenched from 1451°C. Relict olivine is present.*

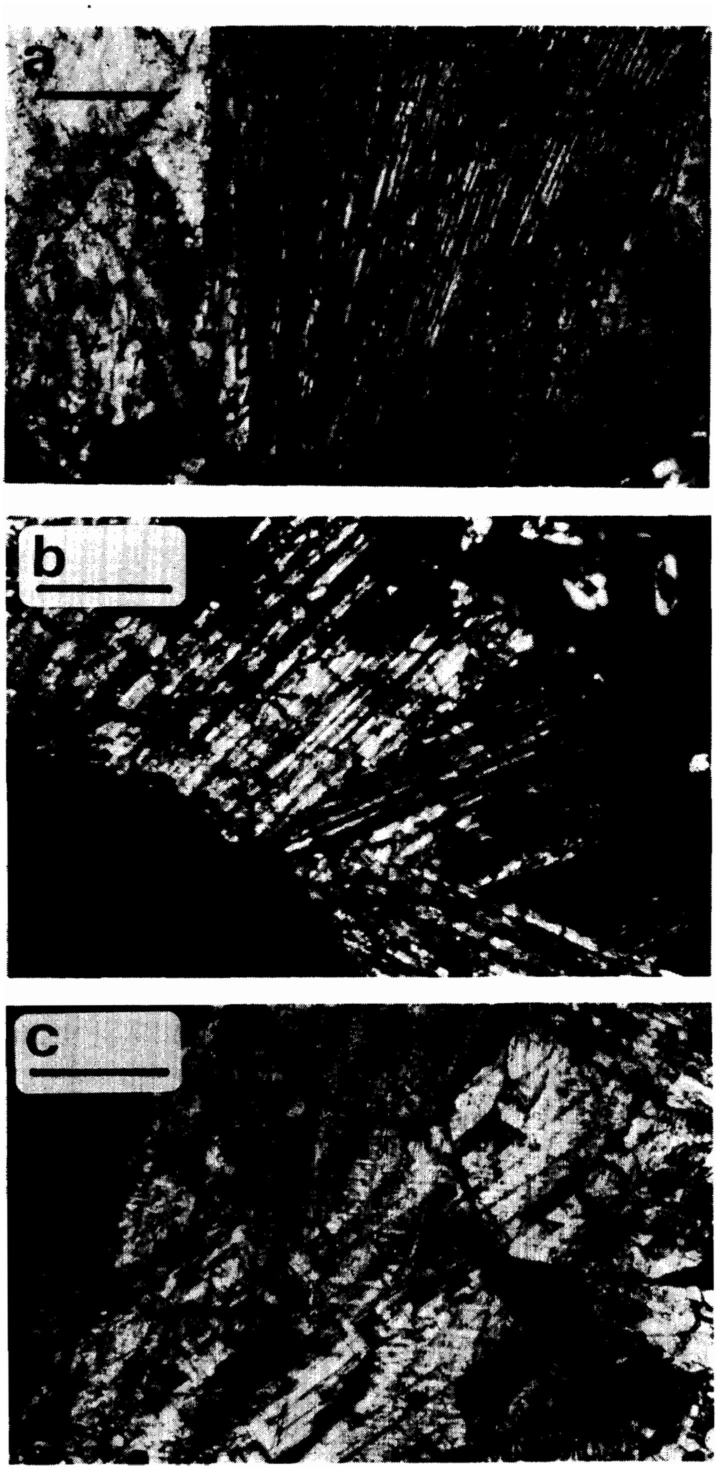

Fig. 3a. *Run 548, cooled from 1549°C. Barred-radial olivine texture.*

Fig. 3b. *Run 539, cooled from 1512°C. Barred-radial olivine texture.*

Fig. 3c. *Run 524, cooled from 1491°C. Barred-radial olivine texture.*

Figs. 3a–l. *Photomicrographs of thin sections of charges cooled at 80–20°C/min from different temperatures of heating on sample 2. Scale bars for Figs.3a to h, Figs. 3i to k and Fig. 3l are 0.2 mm, 0.1 mm and 0.05 mm, respectively.*

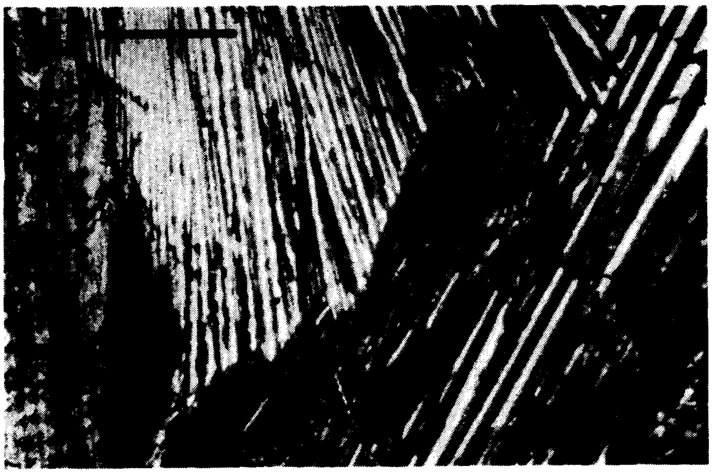

Fig. 3d. Run 536, cooled from 1472°C. Barred-radial olivine texture.

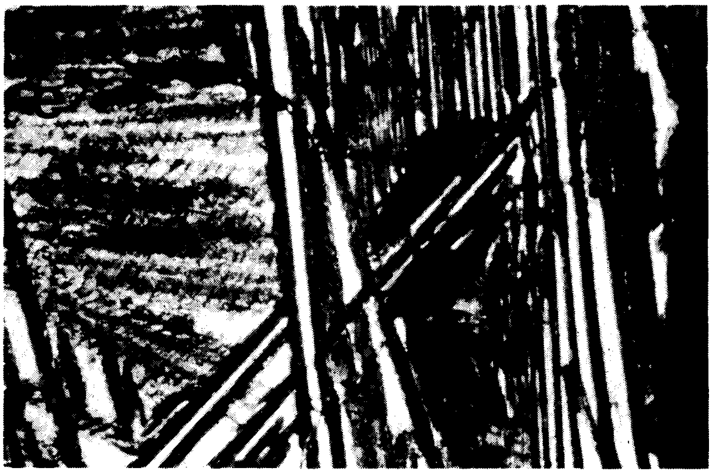

Fig. 3e. Run 547, cooled from 1461°C. Barred-radial olivine texture.

Fig. 3f. Run 519, cooled from 1451°C. Barred-radial olivine texture.

Fig. 3g. *Run 535, cooled from 1445°C. Aggregates of acicular olivine crystals.*

Fig. 3h. *Run 533, cooled from 1440°C. Aggregates of acicular olivine crystals.*

Fig. 3i. *Run 504, cooled from 1429°C. Porphyritic olivine texture.*

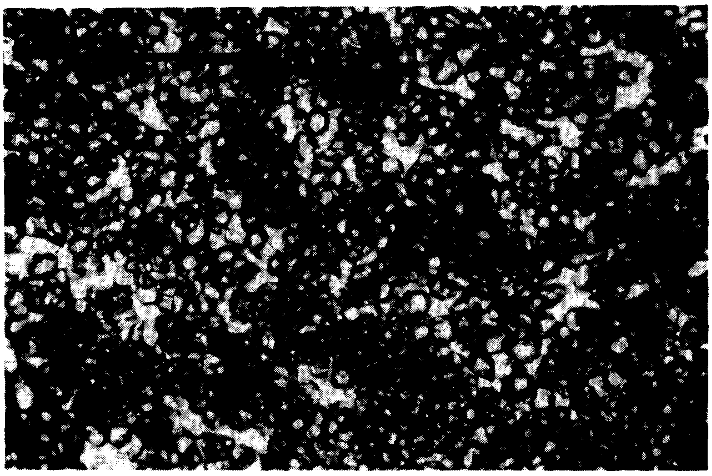

Fig. 3j. *Run 521, cooled from 1414°C. Porphyritic olivine texture.*

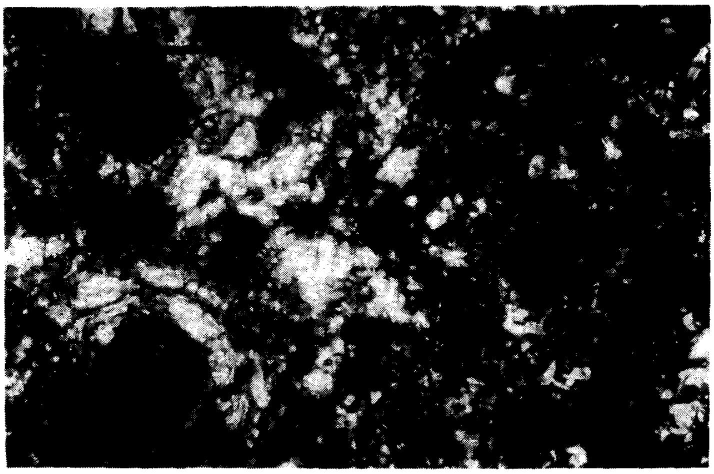

Fig. 3k. *Run 502, cooled from 1387°C. Porphyritic olivine-pyroxene texture.*

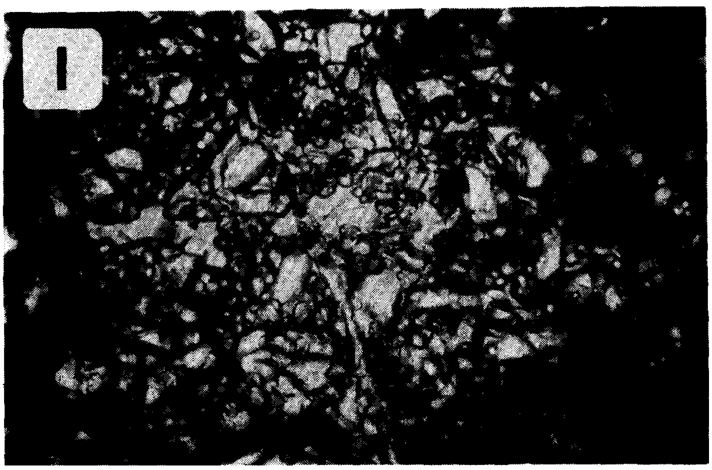

Fig. 3l. *Run 531, cooled from 1370°C. Porphyritic olivine-pyroxene texture.*

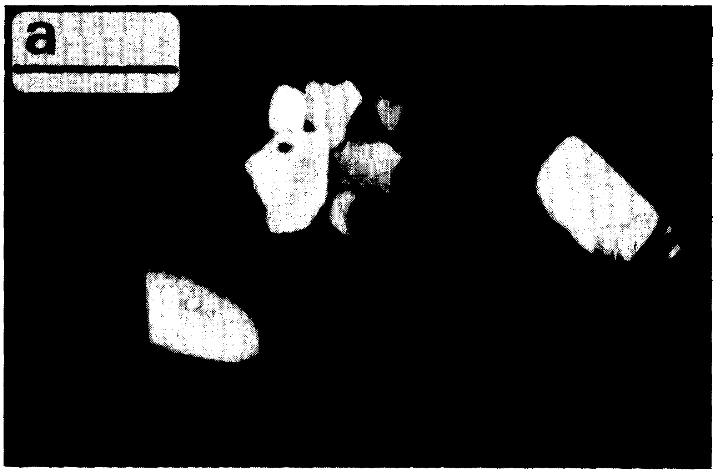

Fig. 4a. *Run 517, quenched from 1451°C. Small amount of quench crystals are present.*

Fig. 4b. *Run 534, quenched from 1445°C. Quench crystals are present.*

Fig. 4c. *Run 532, quenched from 1440°C. Quench crystals are present.*

Figs. 4a–f. *Photomicrographs of thin section of charges quenched from different temperatures of heating on sample 2. Scale bars for Figs. 4a, d, e, Figs. 4b, c, and Fig. 4f are 0.1 mm 0.2 mm and 0.05 mm, respectively.*

Fig. 4d. *Run 503, quenched from 1429°C. Relict olivine rimmed by quench crystals is present.*

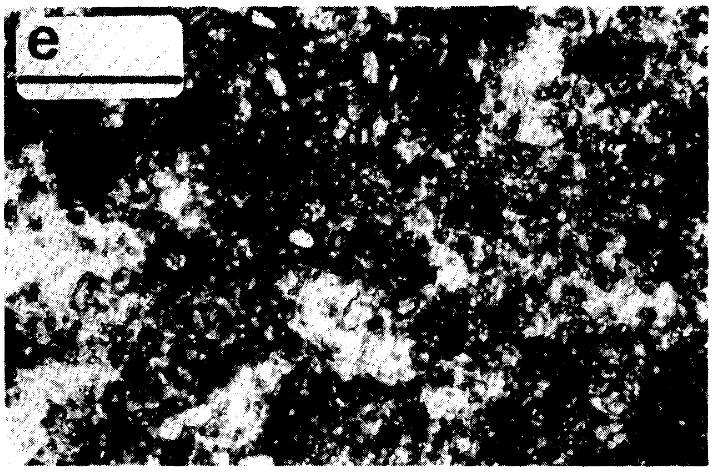

Fig. 4e. *Run 501, quenched from 1387°C. Relict olivine and pyroxene are present.*

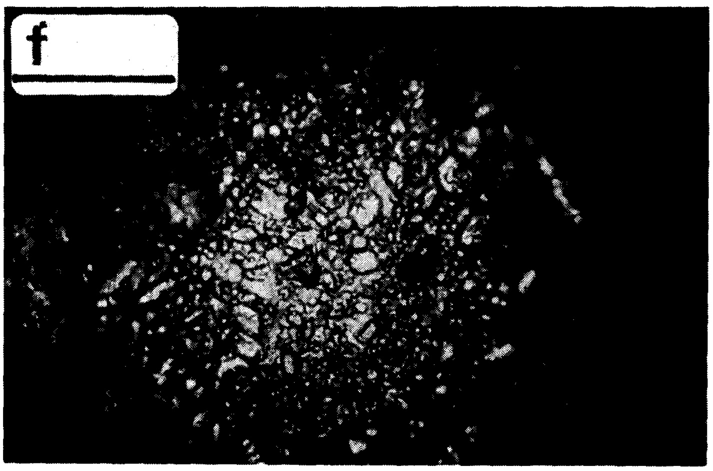

Fig. 4f. *Run 528, quenched from 1352°C. Relict olivine and pyroxene are present.*

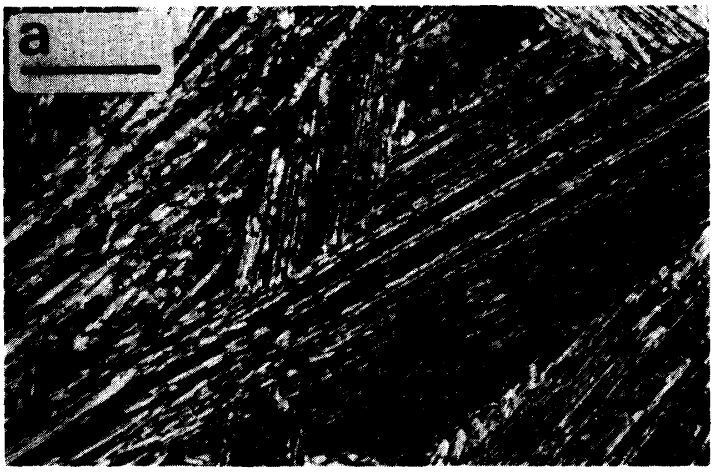

Fig. 5a. Run 570, cooled at 500°C/hr. Barred-radial olivine texture.

Fig. 5b. Same as Fig. 5a. Close-up.

Fig. 5c. Run 573, cooled at 230°C/hr. Barred-radial olivine-pyroxene texture.

Figs. 5a–h. Photomicrographs of thin section of charges cooled with relatively slow cooling rates on sample 2. Scale bars, except in Figs. 5b and f, are 0.4 mm; scale bars for Figs. 5b and f are 0.1 mm.

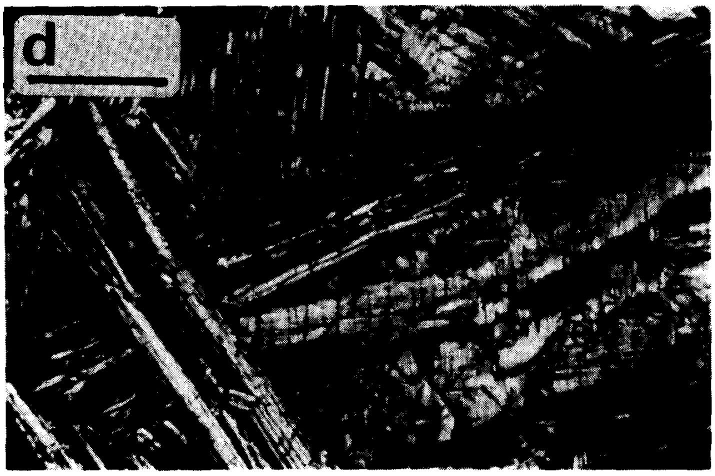

Fig. 5d. *Run 574, cooled at 125°C/hr. Barred-radial olivine texture.*

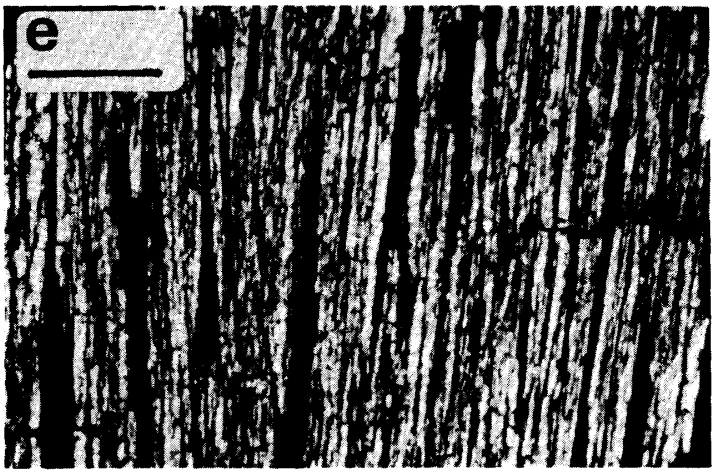

Fig. 5e. *Run 571, cooled at 46°C/hr. Barred-radial pyroxene texture.*

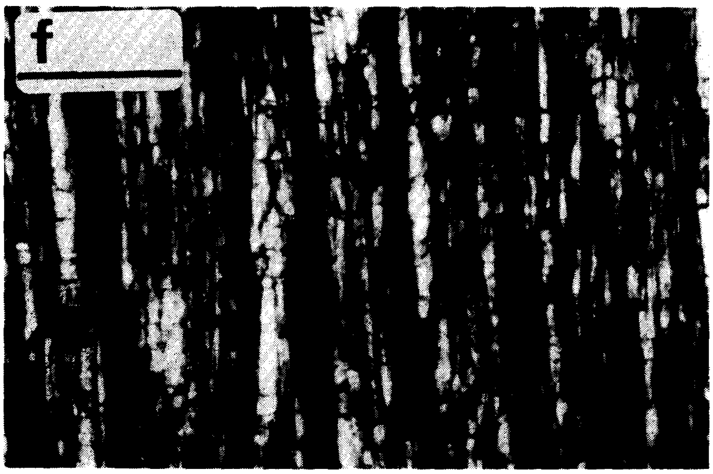

Fig. 5f. *Same as Fig. 5e. Close-up. Polysynthetic twin is easily recognized.*

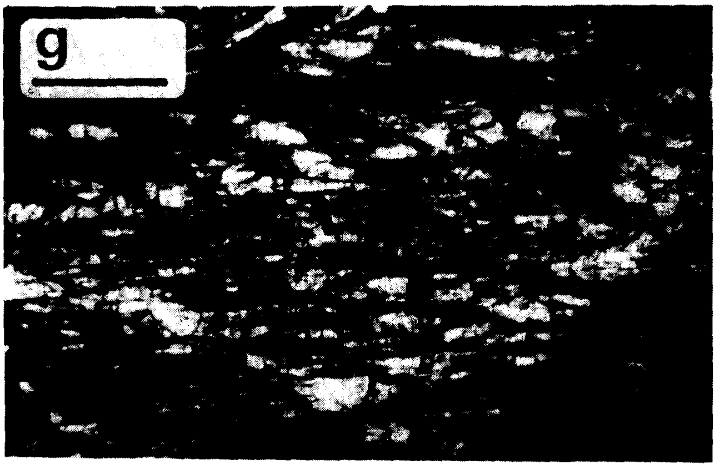

Fig. 5g. *Run 575, cooled at 26°C/hr. Barred-radial pyroxene texture.*

Fig. 5h. *Run 572, cooled at 5.3°C/hr. Comb-like pyroxene (left side) and radial pyroxene (right side) are present.*

If chondrules were formed by local heating of pre-existing materials (*e.g.*, KIEFFER, 1975), porphyritic or microporphyritic texture would be expected to be formed when heating temperature was not high or heating duration was not long so that pre-existing materials were partially melted before cooling. In fact, irregular anhedral olivine crystals with reverse zoning which is considered to be relic minerals were observed (NAGAHARA, submitted). Sodium volatilization experiments (TSUCHIYAMA *et al.*, 1981) also suggest that heating temperature of chondrule formation is not so high; it might be occasionally lower than the liquidus temperature of chondrules, especially for MgO-rich chondrules.

3.2. *Effect of cooling rate*

Figure 5 shows textures of the charges cooled at relatively slow cooling rates (500–5.3°C/hr) from completely melted states. Radial and/or barred olivine crystals are formed in the higher range of cooling rates (500–125°C/hr, Figs. 5a, b, d), whereas radial and/or barred pyroxene, which may be inverted protopyroxene judging from polysynthetic twinning (Fig. 5f), crystallizes in the lower range of cooling rates (46–5.3°C/hr, Figs. 5e–h). With cooling rate 230°C/hr, both olivine and pyroxene crystals are formed (Fig. 5c).

The above results suggest that radial pyroxene texture is formed with cooling rates ranging from about 200°C/hr to less than 5°C/hr on condition that chondrule composition is similar to sample 2. Such rates are much smaller than those for the formation of barred olivine chondrules, about 100°C/min, estimated in the previous experiments. Recently, HEWINS *et al.* (1981) pointed out by experimentation that radial pyroxene chondrules in the Manych LL3 chondrite could have formed with a wide range of cooling rates, from 10°C/hr to over 3000°C/hr. With cooling rates greater than 500°C/hr, however, olivine instead of pyroxene crystallizes in the present experiments. The difference might be due to the difference of chemical compositions of the starting materials.

Acknowledgments

We are grateful to Prof. I. KUSHIRO of the University of Tokyo for critical reading of the manuscript. Thanks are also due to Prof. T. NAGATA of the National Institute of Polar Research, Japan for providing the Yamato chondrite used in the experiments.

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(*Received May 6, 1981*)