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ORIGIN OF METAL-TROILITE AGGREGATES IN SIX ORDINARY CHONDRITES

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***Abstract*:** Coarse metal-troilite aggregates several mms in sizes have been studied in six ordinary chondrites, Yamato (Y)-794006 (L4), Y-793211 (L6), Y-793213 (L6), Y-791629 (H4), Y-791686 (H5), and Y-791555 (H6). In each sample, textures of an aggregate and host meteorite show an evidence for the aggregate being solidified from metal-sulfide melt under a slow cooling condition. Metal and silicate texture in the host meteorite suggest a formation of the metal-sulfide melt by weak or moderate reheating by an impact process on the parent body. Bulk Fe-S compositions of the aggregates show variations in melting temperatures which correlate with petrologic grades of the host meteorites. These evidences suggest that the aggregates formed by impact melting on the "hot" parent bodies by weak or moderate reheating piled on the pre-impact temperatures during thermal metamorphism.

1. Introduction

Ordinary chondrites often include coarse aggregates of metal-troilite grains. In many cases, these grains show an evidence of crystallization from Fe-Ni-S liquids such as dendritic texture, cellular texture, or eutectic mixture of metal-troilite (*cf.* SCOTT, 1982). Since these textures accompany impact loaded texture in their host meteorites, they are interpreted as products of impact melts formed on the parent bodies (*e.g.*, TAYLOR and HEYMANN, 1969; TAYLOR *et al.*, 1979; SCOTT, 1982). The impact process may occur throughout the whole stage of a parent body process. Melting of metal-troilite mixtures in the ordinary chondrite requires at least an eutectic temperature of Fe-Ni-S (about 950°C for kamacite-troilite: HEYMANN, 1967). To obtain such a temperature only by an impact heating of a cold target, the process needs a severe shock condition (STÖFFLER *et al.*, 1991). If the impact heating is loaded on a hot target, a weak or a moderate shock condition is sufficient to cause the melting temperature. Latter possibility has been discussed in the previous studies (*e.g.*, STÖFFLER *et al.*, 1991) and was confirmed by shock experiments (NAKAMURA *et al.*, 1993). However, it is difficult to evaluate the effect of the pre-shock condition included in the natural shock induced textures in chondrites.

In the metallographic study of Moorabie (L3) chondrite, FUJITA and KITAMURA

(1992) estimated both a pre-shock and post-shock temperature of the parent body. The textures observed in the Moorabie including coarse metal-troilite clast and reverse compositional zoning of taenite grains in the host meteorite formed by shock heating of the parent body. The modal composition of the metal-troilite clast and core composition of the taenite allowed to estimate post-shock melting temperature of the metal-troilite (~1000°C) and pre-shock thermal condition of the parent body (>400°C), respectively (FUJITA and KITAMURA, 1992).

The above estimation shows that an impact heating occurred during metamorphism of the parent body. If the similar process produced coarse metal-troilite aggregate in ordinary chondrites of different petrologic types, the effect of the equilibration temperatures must be reflected in the post shock temperature among the different samples suffering a similar shock condition. Based on this assumption, post shock temperatures estimated from the coarse metal-troilite grains and shock condition recorded in the silicate texture (STÖFFLER *et al.*, 1991) were compared among six ordinary chondrites of different petrologic grades.

2. Samples and Experimental Procedure

From the collection of polished thin sections of National Institute of Polar Research, ordinary chondrites containing coarse opaque aggregates were selected; Yamato (Y)-794006 (L4), Y-793211 (L6), Y-793213 (L6), Y-791629 (H4), Y-791686 (H5), and Y-791555 (H6). The petrologic grades of the specimens were estimated by YANAI and KOJIMA (1995). The following experiments mainly describe the texture of the opaque aggregates, opaque grains in the host meteorites, and shock induced texture recorded in the host meteorites. The polished thin sections were studied by optical and scanning electron microscopy and electron probe microanalysis (Jeol-8800 at Institute

Table 1. Characteristic properties of the coarse metal-troilite aggregates and metal-troilite grains in the host rock texture of the six specimens. Metal-troilite ratio of the clast is shown as area per cent of the metal in the metal-troilite assemblage.

Samples	Schock effects	Metal-troilite aggregates	Inclusions
Y-794006 (L4)	Deformed chondrules, mosaicism or undulatory extinction in olivine	Troilite-rich (24%) polycrystalline kamacite	Chondrules, mineral fragments
Y-793211 (L6)	Undulatory extinction in olivine	Metal-rich (52%)	Recrystallized silicate aggregates, pentlandite
Y-793213 (L6)	Undulatory extinction in olivine	Metal-rich (73%) zoned taenite	Recrystallized silicate aggregates, chromite
Y-791629 (H4)	Preffered orientation of chondrules, mosaicism or undulatory extinction in olivine	Troilite-rich	Mineral fragments, chondrule fragments
Y-791686 (H5)	Undulatory extinction in olivine	Metal-rich (58%)	A few fragments of olivine
Y-791555 (H6)	Severely wethered	Metal-rich (80%)	

for Study of the Earth's Interior). Accelerating voltage was 15 kV and beam current was 20 nA. ZAF method was used for the correction of analysis. The degrees of shock metamorphism recorded in the specimens were estimated largely based on optical properties of olivine (STÖFFLER *et al.,* 1991). The metallographic study was carried out on the metal-troilite aggregates and metallic grains in the host meteorites.

3. Results

3.1. Textures of the coarse opaque aggregates

The coarse metal-troilite-rich aggregates are surrounded by normal chondritic texture; they are apparently much larger (several mms in size) than metal-troilite grains in the surrounding host meteorites. Back-scattered electron images of the metal-troilite aggregates are shown in Figs. 1a–f. The coarse aggregates share similar features: (1) metal and troilite are clearly separated, (2) metal regions are mainly composed of kamacite. At the same sample, the metal/troilite ratio and the abundance of minor phases included in the aggregates vary widely. Detailed mineralogical and textural characteristics of the aggregates are summarized in Table 1.

In the Y-794006 (L4), coarse opaque aggregate 5×6 mm in size is largely composed of troilite. Lesser amount of kamacite (Ni ~6.2 wt%) surrounds the troilite portion; troilite: metal ratio is 3.2. Both phases are polycrystalline (Fig. 2a). Thin discontinuous taenite layer, a few μms in thickness is observed at the metal-troilite contact; grain boundaries in troilite portion are usually composed of iron oxide. Both, kamacite and troilite, contain inclusions of chondrules, aggregates and fragments of silicates. The silicate fragments have clastic appearance (Fig. 3a) indicating that no melting occurred after their incorporation into the aggregate. These fragments show undulatory extinctions. The troilite-rich composition of the opaque phase and occurrence of the silicate inclusions in the aggregate resemble a troilite-rich aggregate in an L3 chondrite, Moorabie (FUJITA and KITAMURA, 1992).

In the Y-793211 (L6) (Fig. 1b), an opaque aggregate (2.5×3 mm) is composed of nearly equal amount of kamacite and troilite, troilite: kamacite ratio is 0.92. In this aggregate, kamacite (Ni ~6.3 wt%) occurs in the core of the aggregate, troilite surrounds the kamacite. Silicate inclusions are mainly observed in the troilite area. They are composed of mineral fragments and aggregates of two or three grains of olivine, pyroxene and plagioclase. These fragments and aggregates show clear extinction and subhedral shapes indicating the recrystallization in the aggregate (Fig. 3b). Seemingly, arm of the troilite portion also enclose a host texture. A pentlandite grain is observed at the edge of the troilite area (Fig. 2b). Iron oxide veins observed in troilite and at the contact region of the metal and troilite contain Cu composition.

The appearance of the opaque aggregate in Y-793213 (L6) is closely similar to that of the Y-793211. The opaque aggregate (3×5 mm) is mainly composed of kamacite and smaller amount of troilite is observed in the rim of the metal (Fig. 1c). In the area ratio, troilite: kamacite is 0.37. Kamacite (Ni ~6.3 wt%) includes globules of troilite and zoned taenite ($Ni_{22\text{-}46}$). A chromite is observed in the rim of the aggregate (Fig. 2c). Silicate inclusions are mainly observed in the troilite portion, and their textures are similar to those in Y-793211. Oxide veins are observed in troilite and along

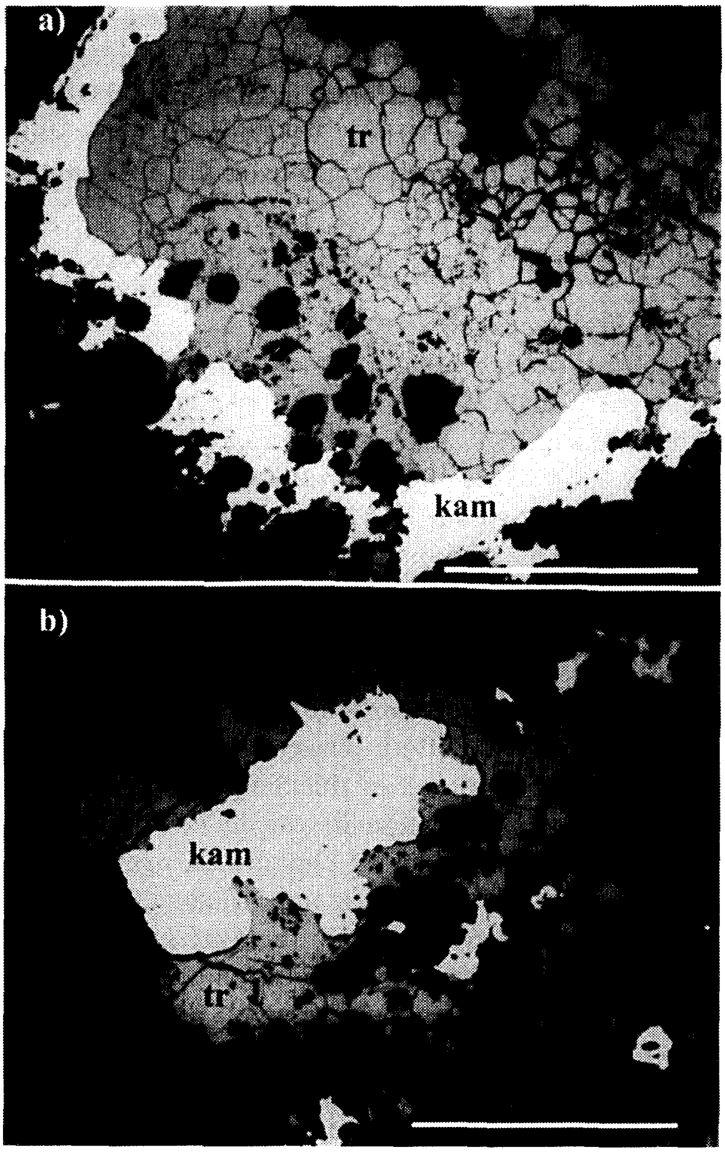

Fig. 1. Back-scattered electron images of the coarse metal-troilite aggregates in six ordinary chondrites, (a) Y-794006 (L4), (b) Y-793211 (L6), (c) Y-793213 (L6), (d) Y-791629 (H4), (e) Y-791686 (H5), (f) Y-791555 (H6). Metal, troilite, and silicate (, and glass) portion appear as white, gray, and black area respectively. Dark gray region in (f) Y-791555 shows the oxide layer. Metal/troilite ratio and the occurrence of silicate (dark) inclusion vary widely among different specimens.
kam: kamacite, tr: troilite. scale bar: 2 mm.

metal-troilite boundary.

In the Y-791629 (H4) (Fig. 1d), an opaque aggregate, 3×5 mm in size, is mainly composed of troilite; kamacite (Ni ~ 6.5 wt%) is less abundant and is observed in the rim of the troilite, while the exfoliation of metal from the thin section makes the metal-troilite ratio ambiguous. Area ratio of the metal in opaque phase is less than 16.4%. Mineral fragments and aggregates of silicates are observed in troilite area. The abundance of silicate inclusions is smaller than those in Y-794006, but their textures

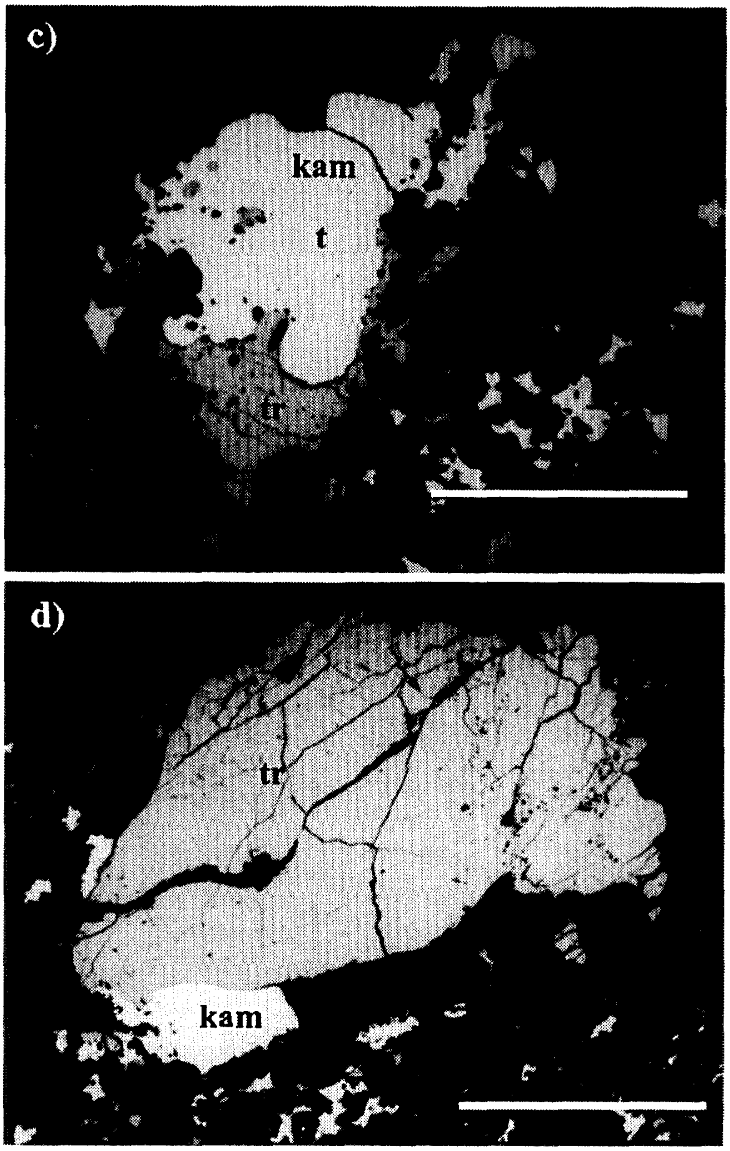

Fig. 1 (continued).

similarly show clastic morphologies.

In the Y-791686 (H5) (Fig. 1e), opaque aggregate, 3×8 mm in size, consists of troilite embedded in kamacite (Ni~6.5 wt%). Troilite: kamacite is ~0.72.

In the Y-791555 (H6), the opaque aggregate and terrestrial iron oxides and sulfates occupy the main portion of the thin section and the silicate portion is observed only as aggregates surrounded by the oxides. The texture of the aggregate (Fig. 1f), troilite surrounded by kamacite (Ni~6.3 wt%) resembles the aggregate in Y-791686. In the area ratio, troilite: kamacite ratio is 0.25. However, the value is not so strict, because a thick layers of iron oxides and sulfates (some 100 μms in width) make the contact between metal and troilite indistinct.

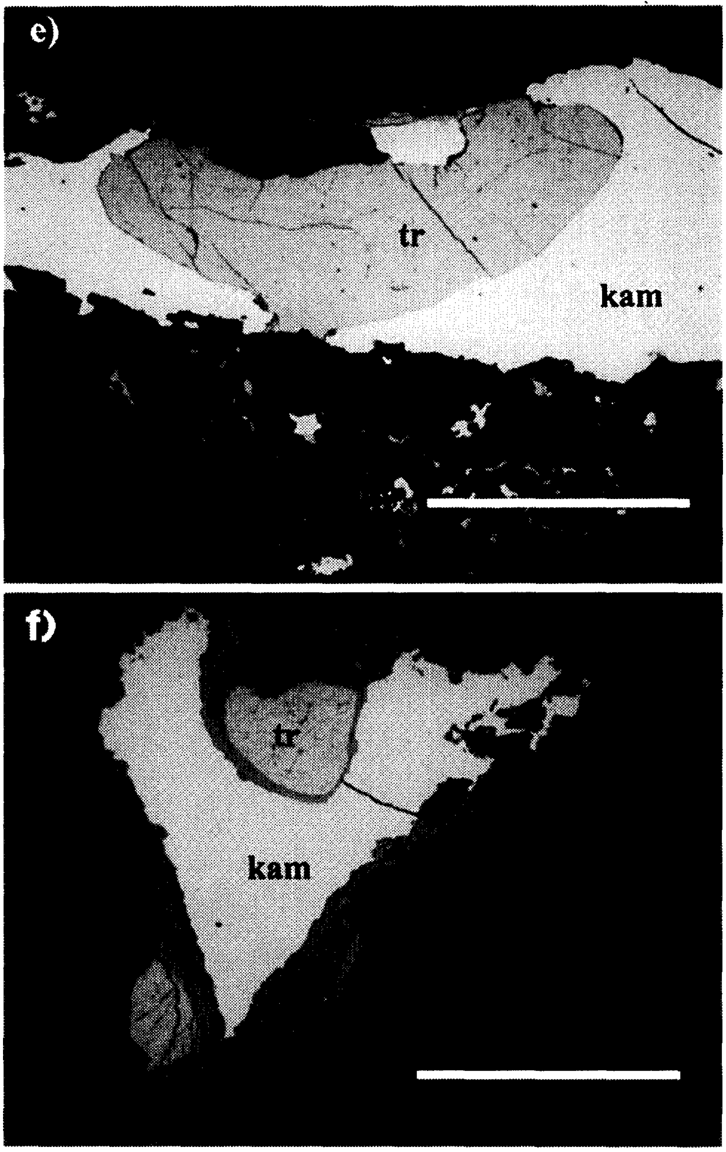

Fig. 1 (continued).

3.2. *Metal-troilite grains in the host meteorites*

In the five specimens, Y-794006 (L4), Y-793211 (L6), Y-793213 (L6), Y-791629 (H4), and Y-791686 (H5), we can observe the chondritic textures surrounding the coarse opaque aggregates. Opaque grains in the host meteorites are generally smaller than 1 mm and the composition of the metal shows wide range of Ni content (Fig. 4).

In the Y-794006 host, kamacite grains show coarse polycrystalline textures similar to those in the aggregate (Fig. 5a). Taenite grains (Ni_{30-46}) show polycrystalline textures composed of several parts with different compositions (Fig. 5b). The texture includes small troilite grains, and some region show a plessitie texture, lamellar micro mixture of kamacite and taenite (Fig. 5c). Adjacent to some metal and troilite grains, fine metal and sulfide droplets are dispersed in the silicate matrix (Fig. 5d).

In the two L6 specimens Y-793211, and Y-793213, general properties of the metal

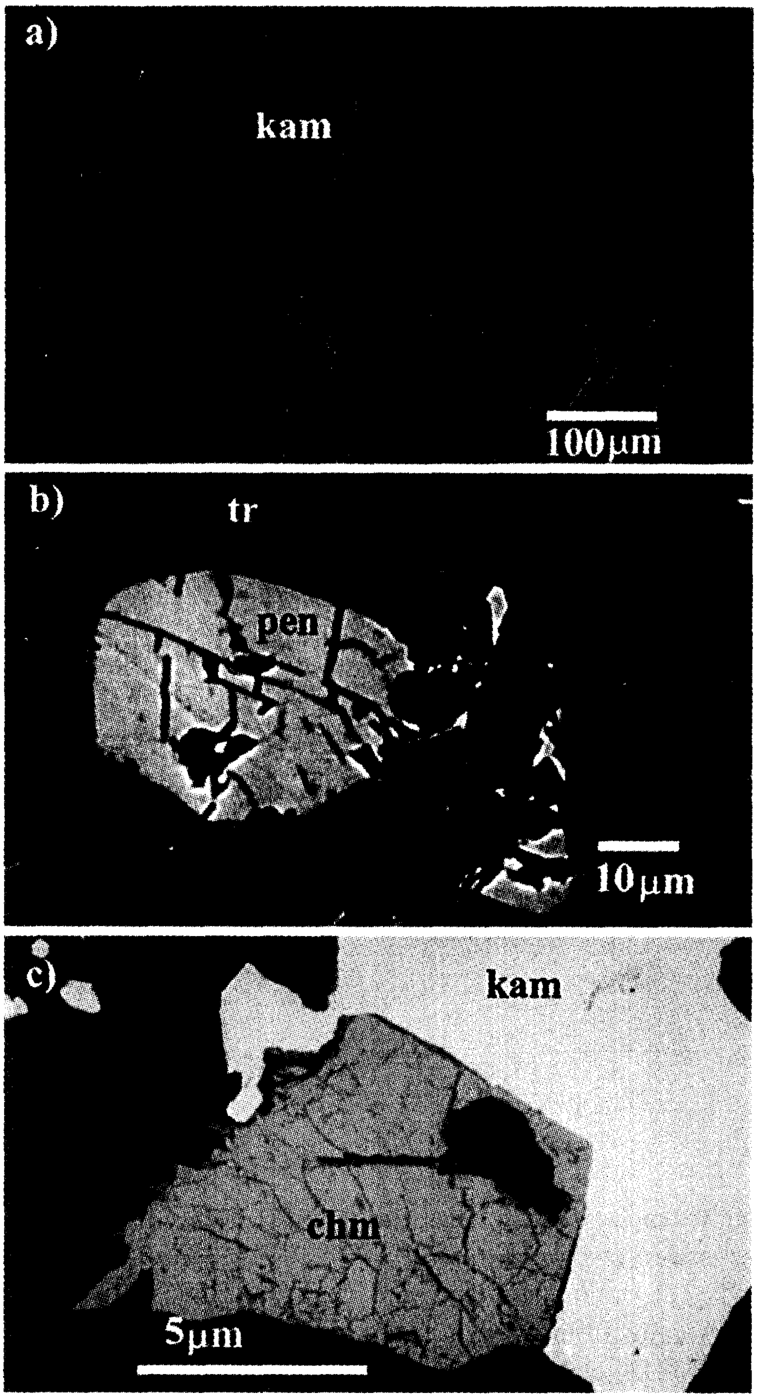

Fig. 2. Characteristics of the opaque phases in the coarse metal-troilite aggregate. Backscattered electron images of opaque aggregates in ordinary chondrites.

(a) Kamacite in the coarse aggregate of Y-794006 (L4). Polycrystallinity of kamacite is reflected in the different contrast of the BSE image.

(b) Pentlandite in the rim of the coarse aggregate in Y-793211 (L6). pen: pentlandite, tr: troilite.

(c) Chromite in the rim of the coarse aggregate in Y-793213 (L6). Crystal surface of the chromite shows a euhedral shape against troilite. chm: chromite, kam: kamacite.

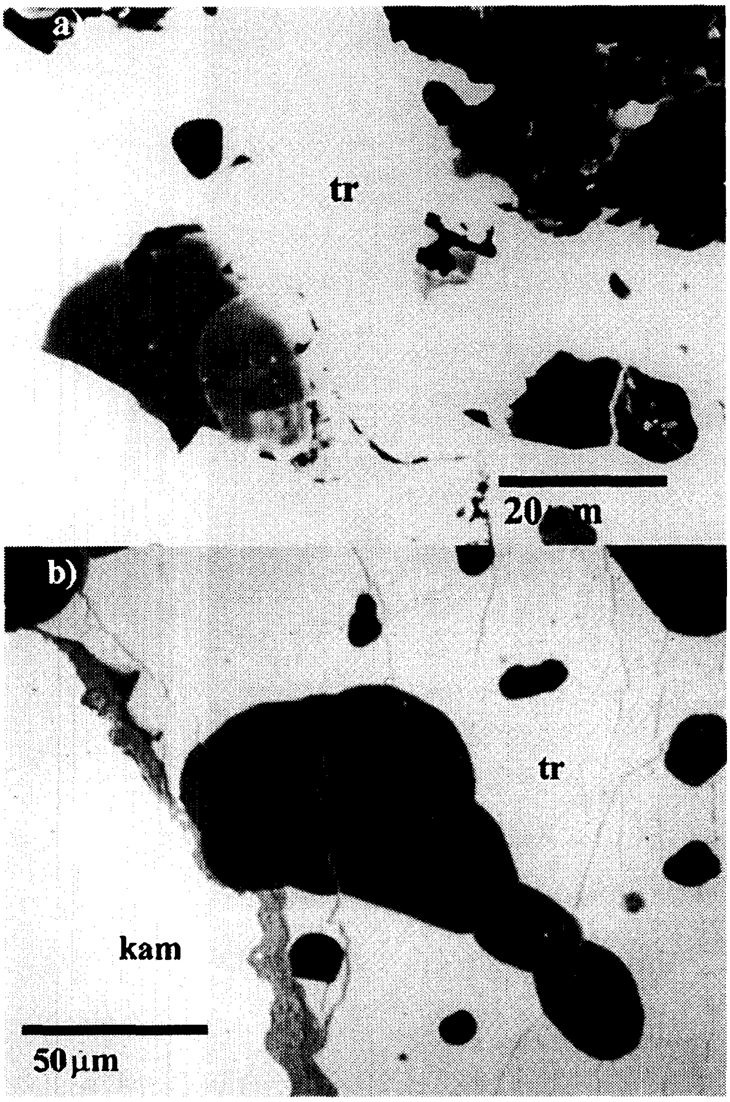

Fig. 3. Back-scattered electron images of silicate inclusions.
(a) In Y-794006 (L4) silicate inclusion shows a broken surface.
(b) In Y-793211 (L6) silicate inclusion shows a rounded shape indicating a recrystallization after the capturation in the opaque aggregate.
ol: olivine, kam: kamacite, tr: troilite

grains are similar to each other. Near the metal-troilite contact, taenite include fine troilite grains embedded in Ni-rich taenite (Fig. 5e). Some portion shows the plessite texture. In Y-793211, some metal-troilite grains include olivine aggregates whose texture show recrystallization in the metal, as was observed in the coarse opaque aggregate. In Y-793213, chromite is observed in some metal grains in the host.

The fine troilite in the taenite, and plessite texture are also observed in the Y-791629 (H4) and Y-791686 (H5). In Y-791686, kamacite includes a coarse chromite grain. In a metal-troilite compound, metal shows a significant compositional zoning ($Ni_{12\text{-}35}$). On the other hand, numerous fine metallic grains are observed in the cracks of silicate texture.

Besides the opaque grains described above, each sample contains more or less iron oxide and sulfate formed by terrestrial weathering. Those oxides are observed near the coarse opaque aggregate, and partially near the opaque grains in the host meteorite, and

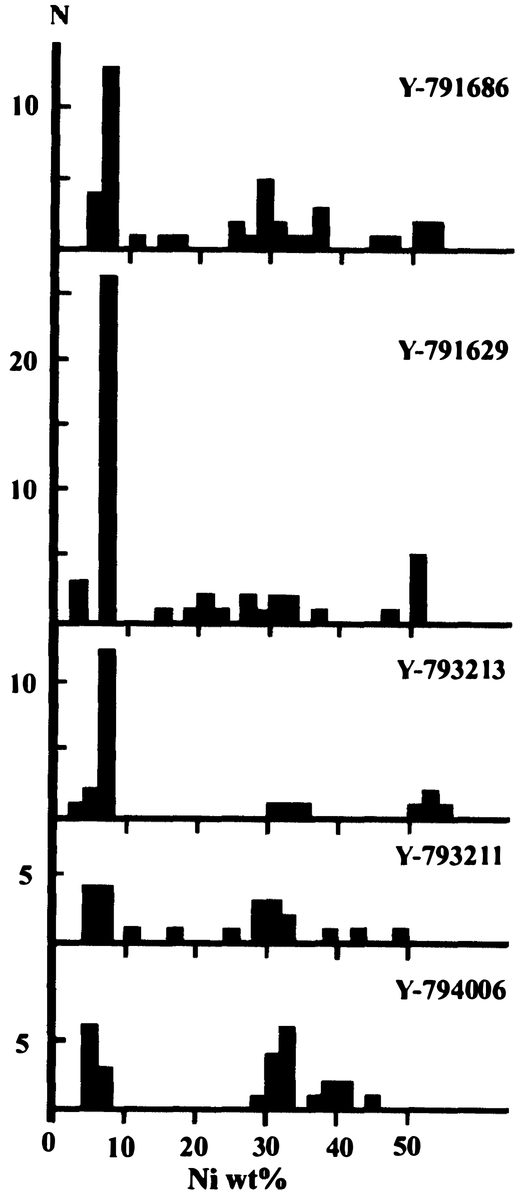

Fig. 4. Histogram of core composition (Ni wt%) of metal grains in the host meteorite of the five chondrites. In each specimens, metal composition shows a wide variation.

as veins crossing the section. In Y-791686 (H5), the outline of the section is rimmed with oxide and numerous oxide veins are observed in the host meteorite. In Y-791555 (H6), the metal, troilite, and silicate portion are enclosed in thick layers of iron oxide and sulfate.

3.3. Evidence of shock effects in the host silicates

As described above, silicate texture is scarcely observed in the section of Y-791555. In the other five specimens, the host textures show the evidence of moderate shock condition.

In the Y-794006 (L4), some chondrules form a complex compound texture (Fig. 6a). Judging from their interaction with matrix, it may be formed by a compression during or after their accretion. Most of olivines in the host meteorite show strong

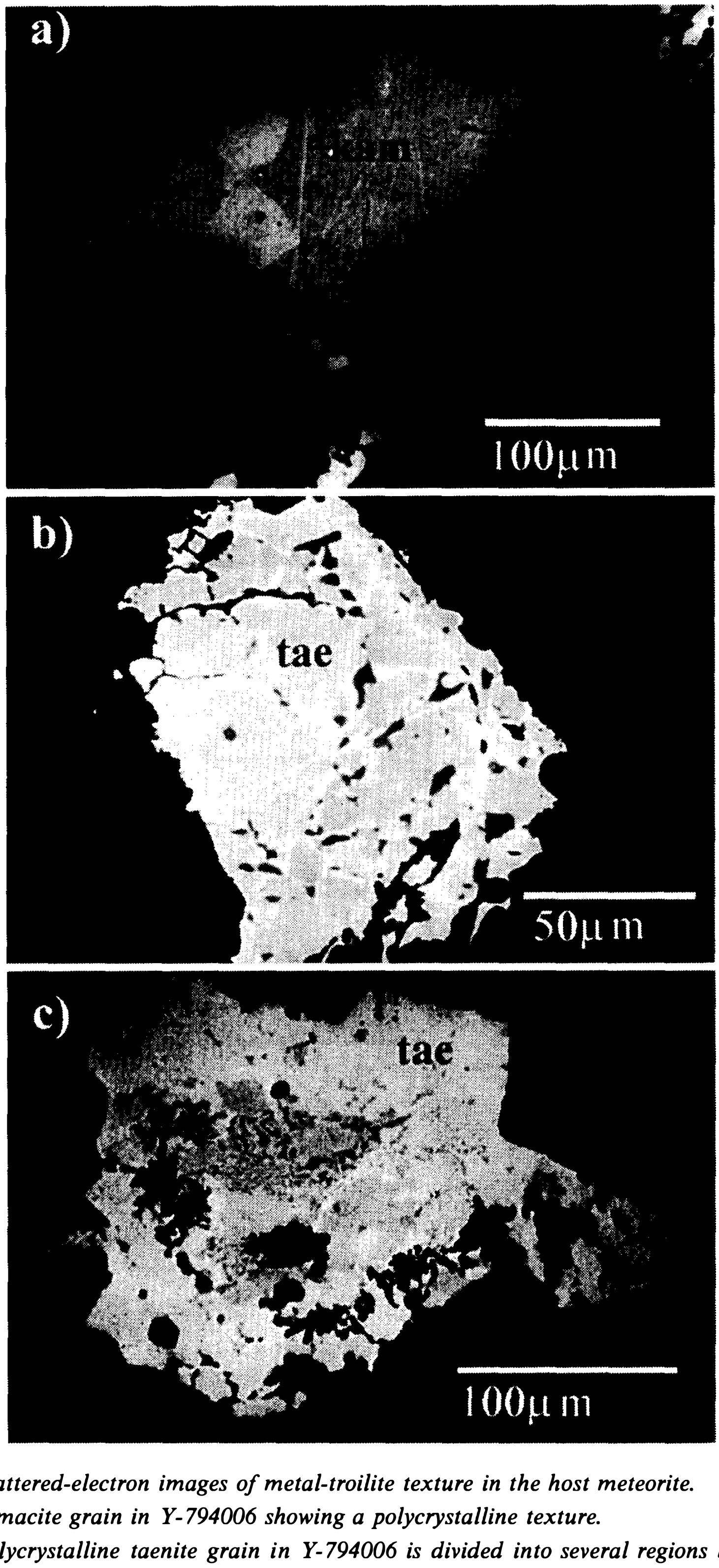

Fig. 5. Backscattered-electron images of metal-troilite texture in the host meteorite.
(a) Kamacite grain in Y-794006 showing a polycrystalline texture.
(b) Pollycrystalline taenite grain in Y-794006 is divided into several regions by the thin high Ni (white) layer including (dark) troilite.
(c) Metal grain in Y-794006 showing a plessitic texture. Core of the grain shows a lamellar micromixture with different Ni contents.

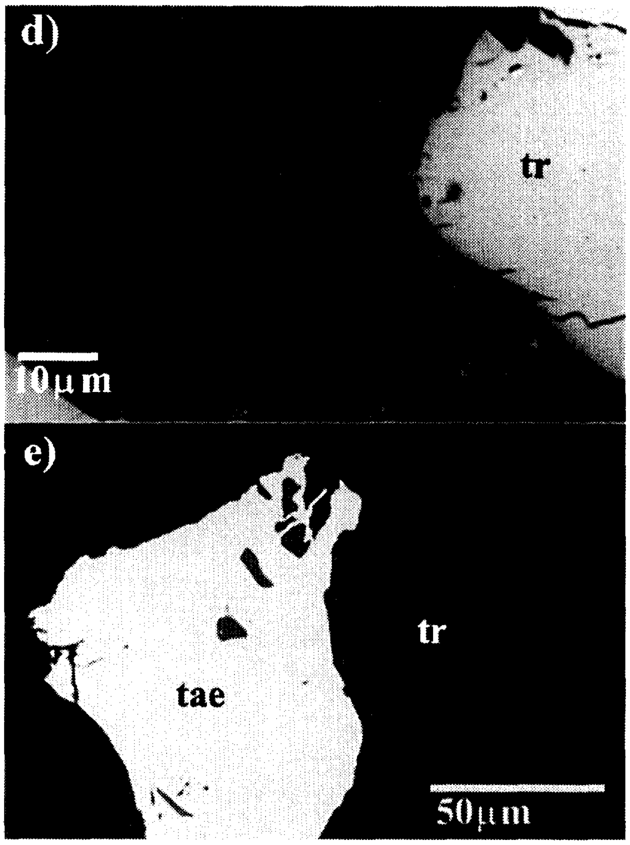

Fig. 5 (continued).

(d) Troilite-rich droplet in Y-794006. Near the metal-troilite grain, fine droplets of metal-troilite are observed in the silicate matrix.

(e) In Y-793211, troilite (dark gray) grains are included in the taenite near the metal-troilite boundary.

tr: troilite, kam: kamacite, tae: taenite.

undulatory extinction and planar fractures. Some grains show mosaicism. In the two L6 specimens, Y-793211 and Y-793213, the evidence of shock effect is rather fewer than in the L4 sample, Y-794006. Many olivines in the host meteorite show undulatory extinctions, while some olivine grains show normal extinctions. Planar fractures are also observed in the olivine, but it is not the common feature. In the scheme of STÖFFLER *et al.* (1991), the Y-794006 (L4) may be classified as shock stage S3-S4, and the Y-793211 (L6) and Y-793213 (L6) may be as S2-S3.

In the host texture of Y-791629 (H4), the evidence of shock effect is similar to those in the Y-794006 (L4). Olivine grains show strong undulatory extinctions and planar fractures, and some grains show mosaicism. Ellipsoidal chondrules (Fig. 6b) and metallic grains show a preferred orientation indicating a post accretion compression possibly by impact process (WASSON, 1985; SNEYD *et al.*, 1988; NAKAMURA *et al.*, 1992). In Y-791686 (H5), olivines in the host meteorite show undulatory extinctions, and some grains show planar fractures. In the scheme of STÖFFLER *et al.* (1991), the Y-791629 (H4) may be classified as shock stage S3-S4, and the Y-791686 (H5) may be as S2-S3.

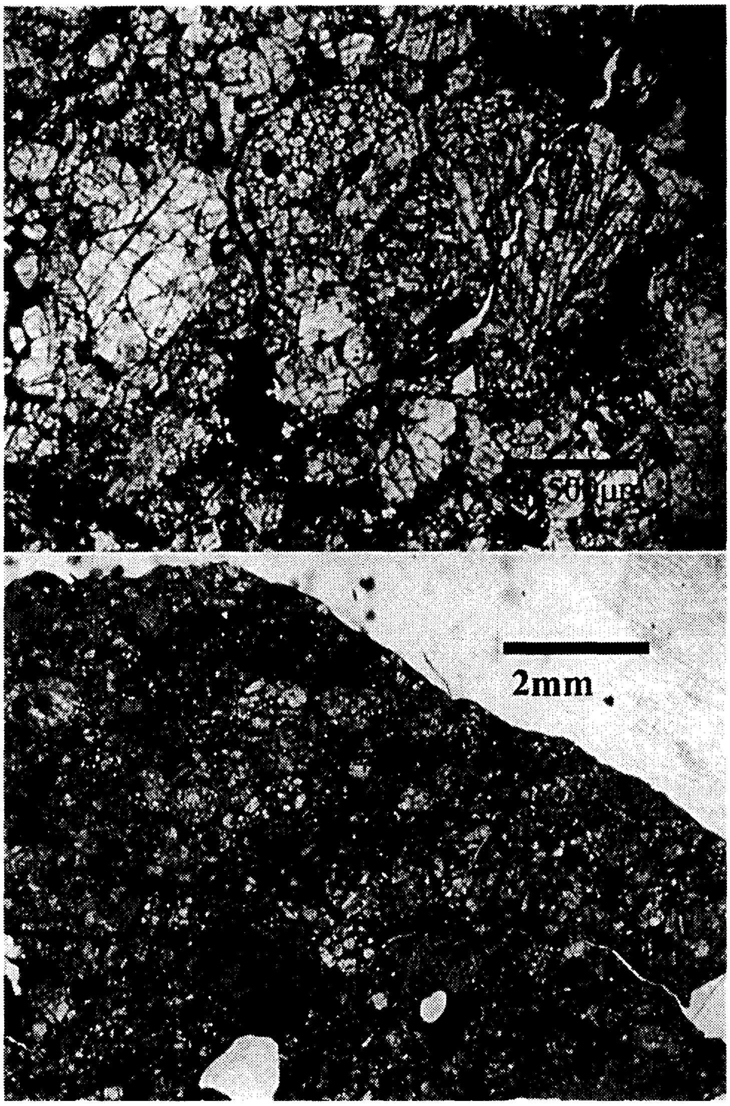

Fig. 6. Optical micrograph of the host meteorite texture in Y-794006 (a) and Y-791629 (b).
(a) Shapes of chondrules show plastic deformation possibly due to compression.
(b) Ellipsoidal chondrules show a preferred orientation; long axes of the chondrules are nearly parallel to the horizontal axis.

4. Discussion

4.1. Origin of aggregates by melting on the parent body

Before discussing the formation mechanism of coarse metal-troilite aggregates, the place of their formation should be considered. From this consideration, we can exclude the frictional fusion in the Earth's atmosphere since the aggregates are not the quenching products. The characteristics of the aggregates, complex boundaries between the aggregates and the host meteorite textures, their compositional difference from the metals in the host meteorite suggests their formation after the accretion of parent bodies.

In some case, formation of coarse metal grains in chondrites is explained by condensation of the metals from vapor phase caused by impact heating (WIDOM *et al.*, 1986). On the other hand, it is suggested that mobilization of sulfur vapor during metamorphism of chondrites may affect the metal-troilite texture (*cf.* LAURETTA *et al.*, 1997). While, for the present case, the occurrence of silicate inclusions in the aggregates cannot be explained by the condensation of metallic region. Nor, the aggregates composed of coarse troilite and kamacite can form by mobilization of sulfur vapor at a subsolidus temperature of metal-troilite. The kamacite-rich composition of the coarse aggregates (containing small but a certain amount of Ni) may not be preserved by sulfurization of adjacent kamacite, nor achieved by vaporization of sulfur from the troilite. Although, loss of sulfur vapor may be included in the possible process, it is hard to explain the formation of the coarse metal-troilite aggregates only by the solid-vapor reaction in the parent bodies.

Another possibility is the crystallization of metal-troilite aggregates from liquid formed in the parent bodies. In the previous estimation of equilibration temperature for ordinary chondrites (*cf.* DODD, 1981), only the highest estimation for the type 6 chondrite exceeds the eutectic temperature of the Fe-S system. Therefore, to cause a partial melting of metal-troilite assemblage, additional heating event must be considered. In many case, coarse metal-troilite aggregates included in the chondrite have been interpreted as products of impact heating on the parent body (*e.g.*, TAYLOR *et al.*, 1979; SCOTT, 1982). Where the post-shock temperature is higher than the eutectic temperature of the Fe-S system, metal-troilite compounds in the chondritic texture begins melting. Then, such liquid concentrates to form a coarse texture.

Metal-troilite aggregates described above have textures being consistent with their formation from impact melts. Each aggregate is distinguished from those of metal-troilite grains in the host meteorites. Firstly, the size of the aggregate several mms in diameter is apparently larger than the normal metal-troilite grains in the host texture. Secondary, metallic phase in the coarse aggregate is composed entirely or predominantly kamacite, while metallic particles in the host meteorites contain considerable amount of taenite. We infer that this difference is due to secondary origin of the coarse aggregate. Partial melting of the metal-troilite grains resulted in formation of Ni-poor liquids, which concentrated to form the coarse metal-troilite aggregates.

The presence of minor phases can also be explained by impact origin of the aggregates. In the five specimens, Y-794006, Y-793211, Y-793213, Y-791629, and Y-791686, the metal-troilite aggregates contain inclusions of silicates which may have been captured by metallic melts. Other minor phase in the coarse aggregates, pentlandite in Y-793211 (L6), and chromite in Y-793213, are probably of igneous origin. In general, sulfide grains in ordinary chondrites are Ni-poor troilites. Ni-rich sulfide can form by crystallization from a Fe-Ni-S liquid. As chromite is soluble in the metal-sulfide liquid, it occurs as accessory phase in some iron meteorites (TESHIMA *et al.*, 1986) or shows a corrosion by troilite in chondrite (BEGEMANN and WLOTZKA, 1969). Chromite grain in the coarse aggregate in Y-793213 (L6) can be crystallized from metal-troilite rich liquid. In Y-793211 (L6), oxidized layer at the contact of the metal and troilite region contains Cu content. We cannot exclude perfectly the possibility of Cu contamination during terrestrial or artificial process. While, the presence of Cu can be explained by the melt origin of the opaque aggregate consistently, since occurrence of native Cu is not extraordinary in reheated chondrites (RUBIN, 1994).

Metal-troilite compounds in the host meteorites also show evidence for melting: fusion droplets of metal-troilite are observed in Y-794006; In the five specimens (Y-

794006, Y-793211, Y-793213, Y-791629, Y-791686), contact region of metal-troilite shows a complicated texture caused by crystallization from liquid. In Y-791686, metal grains are chemically zoned near metal-troilite contacts. Such zoning may be due to crystallization process. As in the coarse aggregates, chromite grains in metal of Y-791686 and Y-793213 is an evidence of melting. We suggest that these observations indicate formation and migration of metal-troilite liquids in the host meteorites. Coarse metal-troilite aggregates were probably formed from such liquids. In Y-791555, the observable region of the host meteorite is not large enough to discuss the origin of the opaque aggregate. However, based on the textural similarity of the opaque aggregate to those in other specimens, we infer the similar origin.

4.2. *Heat source: impact reheating*

The heat source for the melting is often related to impact process. Also in the present case, the host meteorite experienced an impact reheating. In the five specimens, Y-794006 (L4), Y-793211 (L6), Y-793213 (L6), Y-791629 (H4), and Y-791686 (H5), shock induced textures are closely similar to each other in spite of the difference in petrologic grades. Undulatory extinction of olivine observed in the specimens is an evidence of moderate shock process. Preferred orientation of chondrules is an indicator of shock compression after accretion of the parent body (WASSON, 1985; SNEYD *et al.,* 1988; NAKAMURA *et al.,* 1992). On the other hand, metal-troilite grains in the coarse aggregates show no evidence of shock compression. We infer that the coarse metallic aggregates in our specimens are products of impact melt. In the L6 specimens, Y-793211 and Y-793213, the silicate inclusions with the recrystallization texture in the melt show clear extinction indicating their formation after the shock event.

However, the shock level estimated from the silicate texture is not sufficient to form a metal-sulfide melt, if the shock was loaded on the cold meteorite. The range of the temperature increase expected from the shock stage of the specimens (S2–S4) is 20–350 degrees (STÖFFLER *et al.,* 1991), while the lowest temperature needed to cause a melting of kamacite-troilite contact is about 950°C (HEYMANN, 1967), the eutectic temperature of the system Fe-Ni-S (KULLERUD, 1963). Of course, heterogeneous effect of the shock process may cause a localized melting of chondritic texture even though the shock process is weak or moderate one. While, it is also certain that the melting is easy to occur when the high temperature condition of the target meteorite is added on the temperature increase after the shock event. Therefore, it is worth considering the effect of pre-shock temperature included in the post shock temperature reflected in the texture of our samples.

4.3. *Effect of pre-shock temperature of the parent body*

In the study of a shock melting origin of a troilite-rich aggregate in Moorabie (L3) chondrite, FUJITA and KITAMURA (1992) proposed a shock heating during the equilibration stage of the parent body. If the similar process (shock heating in the equilibration stage) occurred in the chondrites of different metamorphic grades, the difference in the equilibration condition must be reflected in the post shock temperature.

In the six specimens showing the similar shock level, the texture of metal-troilite aggregates, especially the aggregates in the L group specimens, such as, Ni poor composition in the metal, separation of metal and troilite area, silicate inclusions, resemble those in the aggregate in Moorabie (L3). We interpret these observations as evidence for a similar origin by shock heating during the metamorphism.

Crystal morphology of the coarse aggregates also implies their formation on the hot parent bodies. If the impact event was loaded on a cold parent body, post shock cooling rate might be rapid enough to form a quenching texture, such as dendritic or eutectic mixture of metal-troilite (SCOTT, 1982). In the present case, the metal and troilite are well separated suggesting a slow cooling rate which can be explained by impact on the hot parent body. If the melting occurs during the equilibration process of the host meteorite, the solidification process of the opaque aggregate is controlled by the cooling rate of the host meteorite, and possibly results in the metal-troilite texture similar to the present samples.

On the other hand, maximum temperature in the impact process reflected on the composition of the coarse aggregate shows a positive correlation with a petrologic grade of the host meteorite. The maximum temperature of the formation process of the coarse aggregates can be estimated from their metal/troilite ratios. Because the bulk content of metallic iron and sulfur in ordinary chondrite is richer in Fe than the eutectic composition of the Fe-S system, iron content in the secondary melt is expected to increase with increasing temperature. When we estimate the maximum temperature for the aggregates based on their positions in the phase diagram of the Fe-S system (*cf.* CRAIG and SCOTT, 1974), the estimated value for the each aggregate shows a positive correlation with petrologic type. For example, in L group specimens, area percent of metal is 15% in Moorabie (L3), 24% in Y-794006 (L4), and 52% in Y-793211 (L6). Based on the phase diagram of the Fe-S system, melting temperature of ~1000°C for Moorabie, 1200°C for Y-794006, and 1350°C for Y-793211 can be estimated. Although these values are very rough (Ni content in the kamacite and loss of sulfur vapor are not considered) and may be higher than the exact values, it may be certain that the melting temperature of the aggregates increase with increasing petrologic grades of host meteorites. Similar correlation is also observed in H group specimens. In spite of the insecurity of the critical metal/troilite ratio, it is certain that the opaque aggregate in the H4 specimen is richer in troilite than those of the H5 and H6 specimens.

The estimated difference in the melting temperature of the metallic aggregates is also consistent with occurrence of the silicate inclusions in the aggregates. In the metal rich aggregates in the L6 samples, silicate inclusions are selectively concentrated in the sulfide portion, while in the L4 sample, both metal and troilite portion include silicate fragments. Such variation can be explained by the difference in the crystallization temperature of the metal; In the Fe-rich melt, metal begins to crystallize at a higher temperature than the eutectic point where troilite begins to crystallize. Thus the silicates are excluded from the metal portion and included in the troilite. When the melt had a composition near the eutectic composition, difference in the crystallization temperature of metal and troilite was not so large to form the selective occurrence of the silicate inclusion. Difference in the melting temperature is also reflected in the texture of the silicate inclusion. In type 4 sample, inclusion shows a fragmental shape indicating no melting of the silicate in the aggregate. While, in the type 6 samples, silicate inclusions show rounded or euhedral outlines indicating recrystallization in the metal-sulfide melt.

It is rather difficult to make a simple explanation for subsolidus phenomena of metallic phase. For plessites observed in the host meteorites, we can explain their origin consistently with the origin of coarse metal-troilite aggregates by a decomposition of taenite (type-I plessite in MASSALSKI *et al.*, 1966), but other explanation by an annealing of α_2 phase (WOOD, 1964, 1967) is also possible. If there is a heterogeneous effect of impact heating in a host meteorite, and the host meteorite experiences multiple impact event, these effects may affect the metallic texture. In the present specimens, reheating events were not strong enough to homogenize the metal compositions (Fig. 4). Heterogeneous heating effect might have a roll in formation of the coarse metallic aggregates in such moderate reheating condition. Whereas, presence of these effects is not conflict severely with the formation of metal-troilite aggregates by weak or moderate reheating during metamorphism of chondrites.

As discussed above, the textures of the present samples indicate a positive correlation between the melting temperatures of the coarse opaque aggregates and petrologic grades of the host meteorites. Such correlation implies that the equilibration process of the parent body plays an important role in the formation process of the melt. Then the variation of the pre-shock temperature of the host meteorite caused a difference in the maximum temperature in the impact process and formed a metal-troilite aggregate of different composition.

It has been suggested that a pre-shock thermal condition of the parent body possibly had an influence on the impact metamorphism of the chondritic texture. However, it is difficult to distinguish the effect of pre-shock condition from the natural sample. The present study proposed a way to qualify an effect of pre-shock condition on the shock metamorphism of chondrite. When the impact process occurs on a parent body during its equilibration stage, a moderate shock process is sufficient to cause a high temperature condition. Namely, it is possible to assume a role of impact effect on the primary stage of thermal metamorphism of chondrite.

5. Summary

Coarse opaque aggregates composed of kamacite and troilite are observed in six ordinary chondrites, Y-794006 (L4), Y-793211 (L6), Y-793213 (L6), Y-791629 (H4), Y-791686 (H5), and Y-791555 (H6). These opaque aggregates were crystallized from melt formed by shock reheating on the parent bodies.

The six specimens, show similar shock induced textures, while the melting temperatures of the opaque aggregates show a positive correlation with their petrologic grades. Such texture can be explained by a shock heating during the equilibration process of the parent body. We suggest that a weak or moderate shock reheating on a parent body during its equilibration stage cause a melting of chondritic material by the effect of pre-shock temperature included in the post shock temperature.

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