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HIGH RESOLUTION X-RAY COMPUTED TOMOGRAPHIC (CT) IMAGES OF CHONDRITES AND A CHONDRULE

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Abstract: In order to study internal textures of meteorites, images were obtained by X-ray computer tomography (CT). This combined high resolution X-ray radiography and computer tomography system belongs to the so-called third generation type with a micro-focus X-ray source and a linear CCD detector with 2048 elements. This allows a spacial resolution of a few μm in the images. Samples examined include the Moorabie meteorite (L3), Allende meteorite (CV3), and a chondrule removed from Allende meteorite. In images, Fe-Ni alloy, troilite, and silicates can be distinguished clearly, and chondrules can be resolved from their Fe-rich rims in Moorabie meteorite. In Allende Fe-Ni alloy, pentlandite, and silicates can be distinguished, and chondrules, CAI's, and matrix can be recognized. Many euhedral crystals, probably olivine and/or pyroxene, were identified in a chondrule, suggesting that the chondrule has a porphyritic texture. In addition to minerals or their assemblages, holes can be identified by the X-ray CT method and were found in chondrules in Allende.

1. Introduction

Textures of meteorites are generally studied by making thin sections and analyzing using an optical microscope, SEM and EPMA. By using this method, samples are often broken when thin sections are made. X-ray computed tomography (CT) may give textural information without breaking the sample, and has potential providing three-dimensional textures from successive images.

Only limited studies have been made by X-ray CT methods on meteorites. MASUDA *et al.* (1986) obtained CT images of chondritic meteorites with an X-ray CT scanner for non-medical use. However, detailed information on the textures cannot be extracted due to the poor spacial resolution (~0.25 mm). HIRANO *et al.* (1990) observed the Allende meteorite (CV3) by monochromatic X-ray CT based on synchrotron radiation (SR). The SR source produces high spacial resolution by beam collimation (down to ~10 μm). Moreover, using monochromatic X-ray source makes it easy to calibrate sample's CT values, which are roughly proportional to X-ray absorption coefficients. Thus chondrules with olivine, matrix, fragments of troilite and pentlandite were distinguished by using quantitative CT values. In addition, they used twenty successive images to examine the three-dimensional structure. However, the three-dimensional structure was not well defined because the slice interval (100 μm) was too large compared with the slice thickness (37 μm). The use of this apparatus at the National Laboratory For High Energy Physics (KEK) Photon Factory is very limited, and only a few samples can be studied.

In the present X-ray CT study, we used commercial new equipment with high spacial resolution. This so-called third generation X-ray CT scanner has a point source of X-rays to give a spacial resolution of several microns in contrast to HIRANO *et al.* (1990) who used collimated X-rays. The point source makes it possible to change the image magnification and to obtain high resolution X-ray CT images of small samples such as chondrules.

2. Experiments

In the present study, a combined high resolution X-ray radiography and computed tomography (CT) system (Nittetsu Elex Co., Ltd.) (YAMAJI *et al.*, 1992) was used to take X-ray CT images. The radiography produces a real-time radiograph of a sample, and was used to determine locations of cross sections for CT images. This system has an X-ray source, a rotation stage, and a detector as shown in Fig. 1.

An X-ray source has a micro-focus with a minimum size of 3 μm, thus giving high resolution X-ray CT images. The X-ray tube is an open type with a tungsten target. No filter was used. The accelerating voltage ranged from 90 to 120 kV. The X-ray tube current ranged from 0.06 to 0.07 mA. The sample is placed on the rotation stage and rotated. At each rotation angle the X-ray absorption is recorded. If a sample is rotated at intervals of 1 degree, 180 projections are obtained. From these data, a cross section is constructed by a filtered back projection method (FBP). Images made of 1024×1024 pixels were constructed. The difference of the X-ray absorption appears as the difference of CT values in the image. When a mineral has larger X-ray absorption, its CT value is large, and its image is brighter. Quantitative calibration of the CT values was not made in the present study.

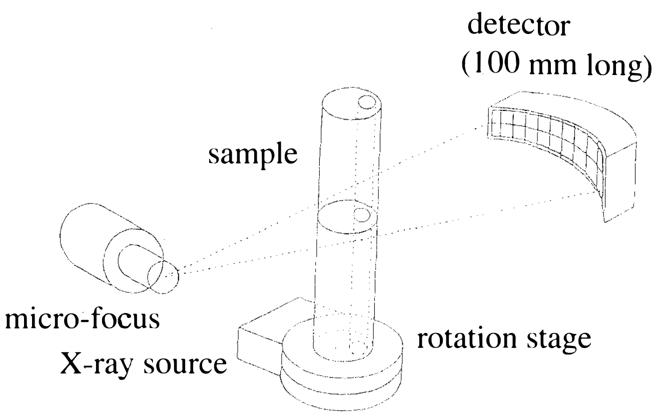

Fig. 1. A schematic illustration of the high resolution X-ray radiography and CT system used. The length of the linear detector is 100 mm, and the distance between the X-ray source and detector can be changed from 220 mm to 1500 mm. The rotation stage can be moved between the X-ray source and detector to obtain different magnifications.

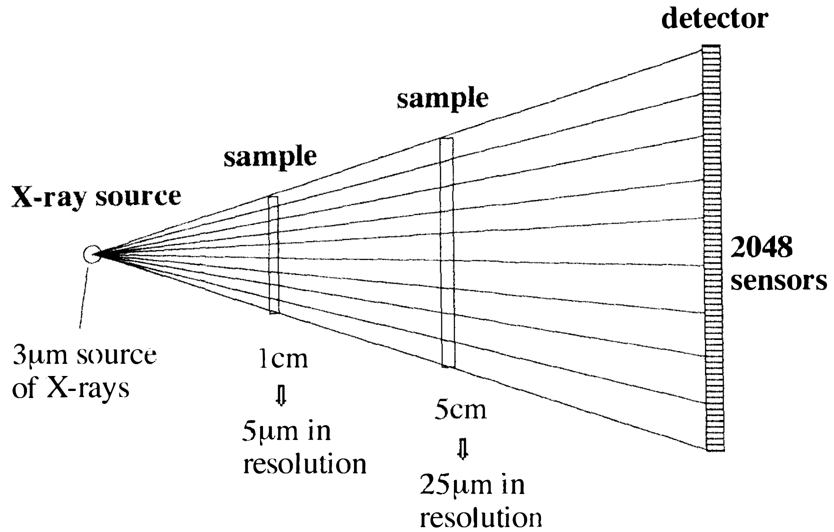

Fig. 2. A schematic illustration of the linear detector and sample sizes to show the relations between spacial resolution of images and magnification.

This system has a linear detector (Fig. 2). High resolution X-ray CT images can be obtained by using this detector made of 2048 CCD elements. Because the length of this detector is 100 mm, the maximum size of a sample is 100 mm. The spacial resolution is determined by the number of detector elements, the width of a slice of the image, the magnification of a sample (thus, the size of the sample), and the size of the X-ray source. If the number of the detector elements is increased or the slice thickness is decreased, high resolution X-ray CT images are obtained. When the size of a sample is 5 cm and all of 2048 sensors are used efficiently, the resolution is about 25 μm, but when the size of a sample is 1 cm, the resolution is about 5 μm. Thus the spacial resolution increases with increasing the magnification. However, the actual resolution is limited by the size of the X-ray source. With the minimum X-ray source of 3 μm in the present system, the spacial resolution is limited to several μm.

The Moorabie (L3 chondrite) and Allende (CV3 chondrite) meteorites were used as representative samples of ordinary and carbonaceous unequilibrated chondrites, respectively. They were cut into cylinders of 8 mm and 10 mm in diameter, respectively, to remove artifacts in their X-ray CT images. If the shape of a sample is irregular, good X-ray CT images cannot be obtained because different X-ray absorbed signals of the sample and the empty space (air) are recorded while rotating the sample. In this case, artifacts, such as halation around a material with large absorption, appears (Fig. 3).

The Moorabie and Allende meteorite samples were rotated at 0.36° intervals, and 500 projections were obtained. Exposure times required for one projection were 4 and 10 s for Moorabie and Allende, respectively, giving a total recording time of about 33 and 83 min, respectively. It takes about 4 min to reconstruct a cross section from 500 projections by FBP. X-ray CT images of each meteorite were taken as slices with 20 and 10 μm thickness, respectively. The slice thickness can be changed by using a slit located between the X-ray source and the sample. The exposure times and thick-

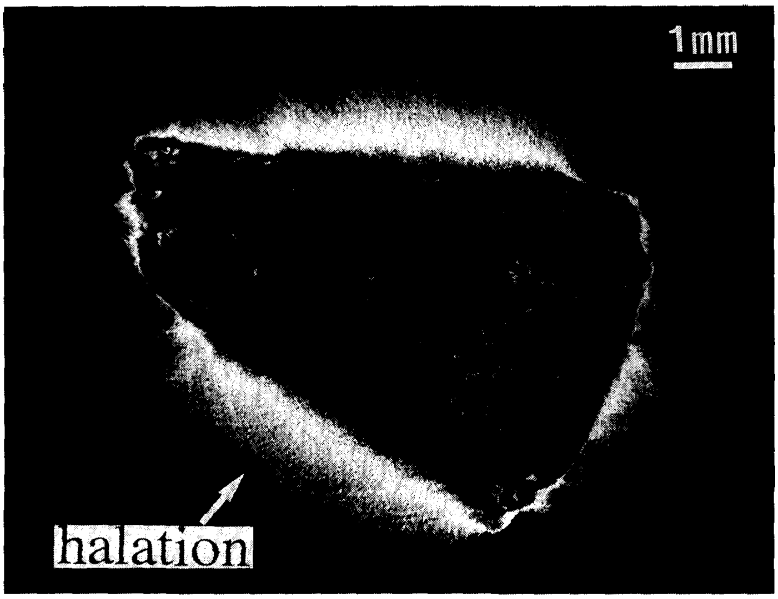

Fig. 3. An X-ray CT image showing artifacts (halation) due to an irregular sample shape (Moorabie meteorite).

nesses were determined by adjustment to obtain the best images. CT images of Moorabie and Allende meteorites were taken with magnifications of 11 and 8, respectively. Thus, the spacial resolutions were about 4 and 6 μm, respectively. After imaging, the samples were cut very carefully to obtain the surface which represents the same position as slices of their X-ray CT images. Polished thin sections were then made for observation under an optical microscope, an SEM/EPMA (JEOL 733, accelerating voltage of 15 kV), and an X-ray microscope (HORIBA, XGT-2000V, accelerating voltage of 30 kV). We compared these images with the X-ray CT images to evaluate what features can be identified in the X-ray CT images.

A 2.5 mm chondrule removed from Allende meteorite by the freeze-thaw method was also studied. This sample was rotated at intervals of 0.36 degree and 500 projections were obtained (4 s/projection). An X-ray CT image was taken as a slice with 50 μm thickness. The images of this sample were taken with a large magnification (about 30 times) to observe its detailed internal texture. This magnification formally gives small spacial resolution (2 μm), but effective resolution is limited by the slice thickness. A polished thin section was not prepared for this sample.

3. Results and Discussions

3.1. Moorabie chondrite (L3)

Figure 4a shows an X-ray CT image of Moorabie meteorite. In Figs. 4b and c, micrographs of the polished thin section under a reflecting and transmitted polarizing microscope are also shown, respectively. In the CT image, bright areas are generally Fe-rich materials because of their large X-ray absorption. A concentric ring pattern in the CT image is an artifact which is made when the sample is rotated. The sample is

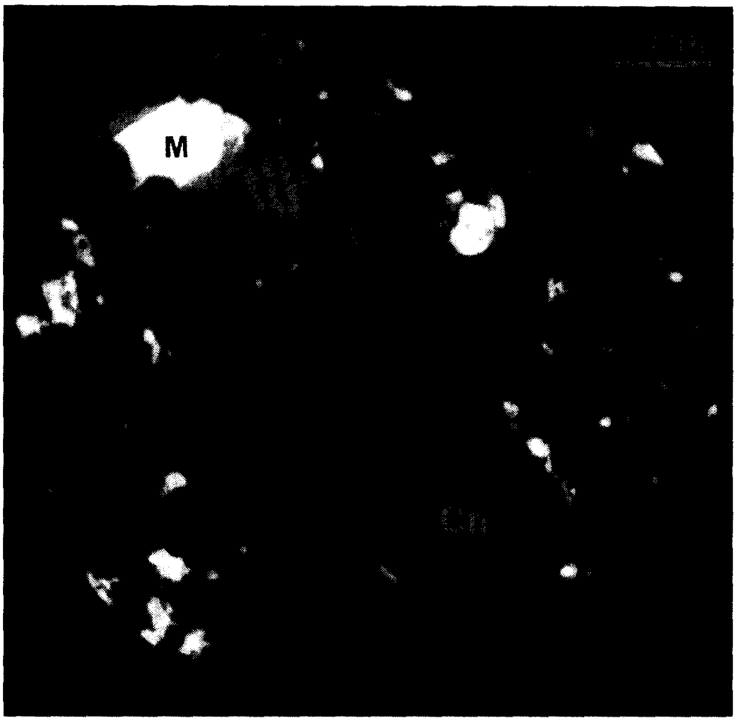

Fig. 4a.

Fig. 4b.

composed of three materials with different degrees of X-ray absorption shown as white, gray, and dark areas. If the X-ray CT image is compared with the reflecting microscope image (Fig. 4b), it is apparent that the white, gray, and dark materials correspond to Fe-Ni alloy, troilite, and silicates, respectively. Kamacite and taenite are pre-

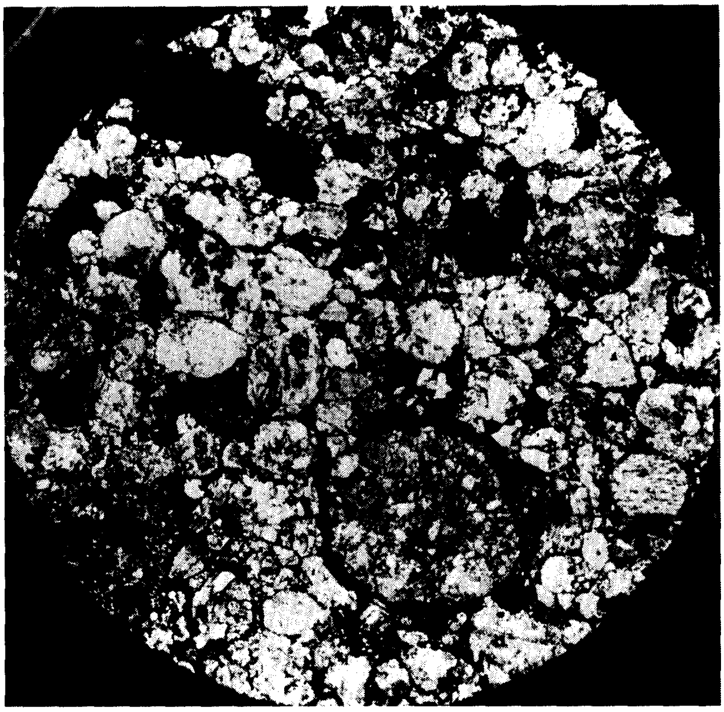

Fig. 4c.

Fig. 4a–c. Images of Moorabie meteorite (8 mm in diameter). (a) An X-ray CT image (20 μm slice thickness, accelerating voltage of 110 kV, and tube current of 0.07 mA) (M = Fe-Ni alloy, Tr = troilite, Ch = chondrule). (b) A reflected light micrograph of the surface almost identical to that of the X-ray CT image. (c) A cross polarized transmitted light micrograph of the same surface.

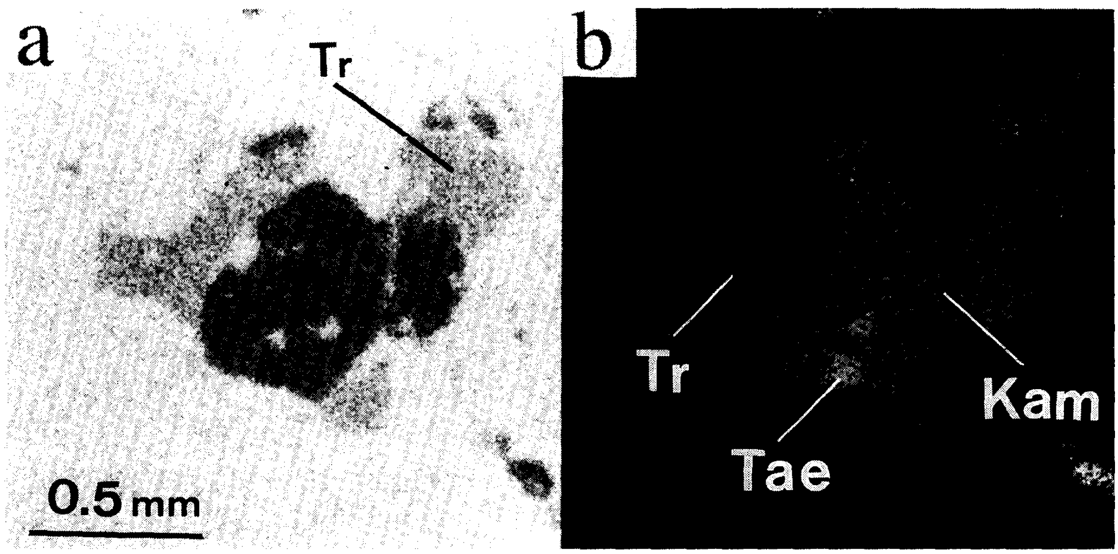

Fig. 5. Images of kamacite and taenite in the Moorabie meteorite using an X-ray microscope (Tr = troilite, Tae = taenite, Kam = kamacite). (a) An X-ray transmission image of Fe-Ni alloy and troilite. (b) Combined mapping by fluorescent X-rays of Fe, Ni, and S in the same position as (a) showing taenite, kamacite, and troilite.

sent as the Fe-Ni alloy (Fig. 5), but they cannot be distinguished in the X-ray CT image. Silicate minerals, such as olivine and pyroxene, also cannot be distinguished because (1) the difference in the X-ray absorption is not large, and/or (2) the magnification is not enough to identify small mineral grains.

Some chondrules can be recognized if they are surrounded by FeS or Fe -rich rims. For example, a large chondrule in the lower right part of the photograph (Fig. 4a) is easily seen. However, identification of some chondrules without such rims is difficult (such as at the lower left of the sample in Fig. 4c), because the X-ray absorption difference between each chondrule is very small.

3.2. Allende chondrite (CV3)

Figure 6a shows an X-ray CT image of Allende meteorite. In Fig. 6b and c, micrographs of the polished thin section under a reflecting and transmitted polarizing microscopes, respectively, are shown. In the CT image the sample is composed roughly of white, gray, and dark materials as in the case of Moorabie. Again, the concentric ring pattern is an artifact. An analysis of its polished thin section by an EPMA showed that white, gray, and dark parts in Fig. 6a correspond to metal, pentlandite, and silicates, respectively.

In this meteorite the dark silicate parts can be subdivided into several materials by different degrees of X-ray absorption although the contrast is small. In Fig. 6a some round and irregular areas, which correspond to chondrules and CAI's, respectively, can be seen. They are confirmed by the thin section image (Fig. 6c). The matrix, chondrules, and CAI's can be distinguished in the X-ray CT image because the matrix

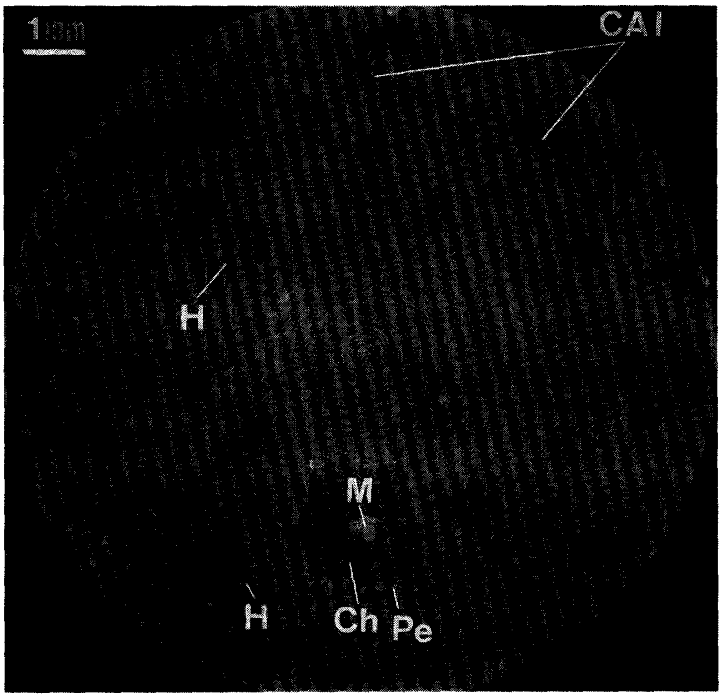

Fig. 6a.

Fig. 6b.

Fig. 6c.

Fig. 6a–c. Images of Allende meteorite (10 mm in diameter). (a) An X-ray CT image (10 μm slice thickness, accelerating voltage of 90 kV, and tube current of 0.07 mA) (H = hole, M = metal, Ch = chondrule, Pe = pentlandite). (b) A reflected light micrograph of the surface almost identical to that of the X-ray CT image. (c) A cross polarized transmitted light micrograph of the same surface.

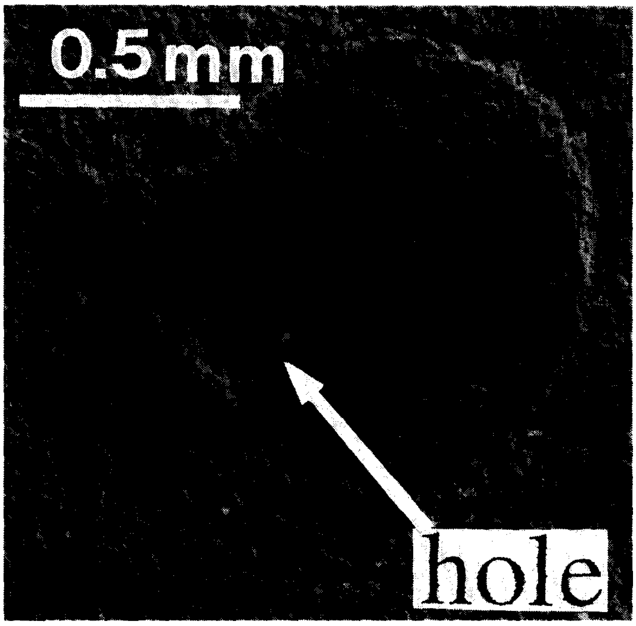

Fig. 7. A SEM micrograph of a hole in the lower chondrule of Allende meteorite (Fig. 6a) recognized during grinding of the sample.

has a higher FeO content than that of chondrules and CAI's. However, individual silicate minerals such as olivine and pyroxene cannot be distinguished as in the case of Moorabie meteorite.

In the X-ray CT image, small black areas are also recognized within chondrules (arrows in Fig. 6a labeled 'H'). These areas have very low density, and in fact, holes can be seen in the thin section at the same positions as in the X-ray CT image. However, there is a possibility that a material was lost when the thin section was made. This possibility can be eliminated because we observed these holes (Fig. 7) when we were grinding the sample during the process of making the thin section.

3.3. A chondrule in the Allende chondrite

Figure 8 shows an X-ray CT image of a chondrule removed from the Allende meteorite. Because of the large magnification of the sample, high spacial resolution was obtained, and thus smaller structures can be seen. Although the polished thin section has not yet been prepared for this sample, the surrounding white areas are probably FeS-rich rims. The CT image strongly suggests that this chondrule has a porphyritic texture. Most crystal grains can be identified by bright rims. These crystals may be olivine or pyroxene which can not be distinguished because of their small X-ray absorption difference. The bright rims correspond to FeO-rich olivine or CaO-rich pyroxene. Moreover, dark portions which may correspond to holes are seen inside the chondrule as in the case of Allende meteorite. Strictly speaking, CT values must be calibrated when we identify materials quantitatively, because they may change by conditions (mainly by the accelerating voltage). In the present experiments CT values were not calibrated. However, it is certain that the dark portions must be holes or materials with extreamly lower X-ray absorption coefficients than silicates, such as

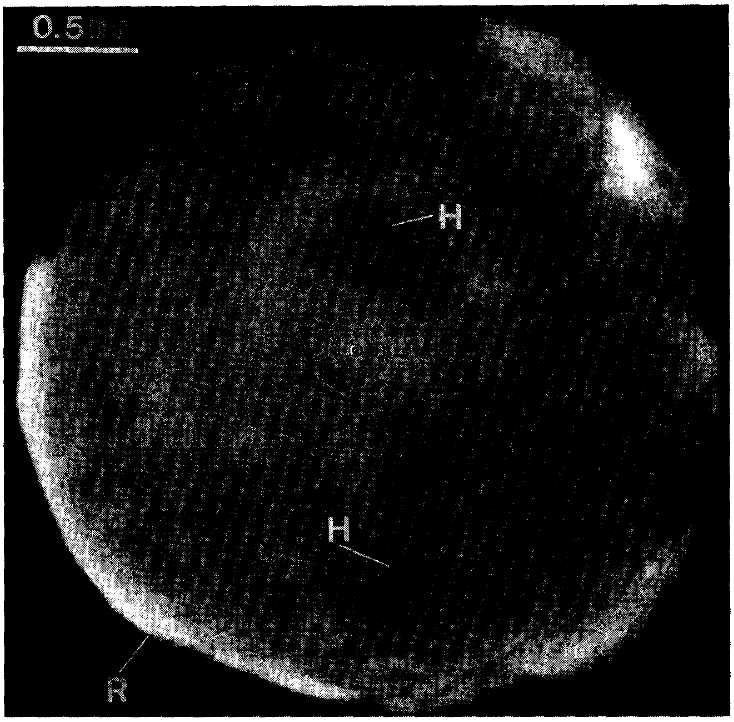

Fig. 8. An X-ray CT image of a chondrule removed from Allende meteorite (2.5 mm in diameter, 50 μm slice thickness, accelerating voltage of 120 kV, and tube current of 0.06 mA), showing a porphyritic texture and low density materials (probably holes) (H= low density material, probably hole, R=FeS-rich rim).

graphite, because the CT values are much smaller than those of the surrounding silicates and similar to those of air.

Holes can be usually observed in thin sections of chondritic meteorites. It has been generally considered that they are not real holes, but some grains were lost when making thin sections. However, the present results (Figs. 6a and 8) strongly suggest that holes are present in chondrules. There are three possibilities as origin of holes in chondrules; (1) during a cooling stage of chondrule formation, the outer portion of a chondrule melt droplet was solidified at first, and then holes were made due to shrinkage of the inner portion by further solidification, (2) when a chondrule droplet was made by heating of a dust fall, the surrounding gas was trapped into the chondrules, or (3) bubbles were formed by boiling when the vapor pressure of a volatile element in a chondrule droplet became higher than the nebula pressure.

It was confirmed that the present X-ray CT technique can give new information, such as about holes, as well as it is available to observe internal textures of chondrites and chondrules. Three-dimensional textures were also successfully reconstructed by taking successive X-ray CT images using a different type of detector combined with image analysis techniques (KONDO, 1996).

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