METALLOGRAPHIC AND MAGNETIC PROPERTIES OF A YAMATO IRON METEORITE--YAMATO-75-105

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Abstract: A Yamato iron meteroite, Yamato-75-105, examined chemically, metallographically and magnetically, has revealed that the major elements of the metal base of this iron meteorite are 5.65% Ni, 1.0% P, and 0.52% Co, in addition to Fe occupying the most parts. From the chemical composition and the microstructure, this iron meteorite can be classified as a reheated hexahedrite, *i.e.* a Ni-poor ataxite. An "ablation zone" about 2 mm in thickness on the flat surface indicates an extensive reheating on entry into the earth's atmosphere although traces of the original single-crystal features remain.

Within the matrix of kamacite (95% Fe and 5% Ni) composition, Fe-Ni phosphide (schribersite; 75% Fe, 10% Ni and 15% P) grains are enveloped by high-P kamacite of α-phase (91% Fe, 7% Ni and 2%P). These structures suggest that this meteorite specimen was reheated to above 1000°C. The acicular grain structure of the kamacite matrix indicates a rapid cooling rate after the reheating. Both metallographic and magnetic analyses have consistently revealed the above-mentioned conclusion.

1. Introduction

The Yamato Mountains field party of the 16th Japanese Antarctic Research Expedition (1975–1976) has found and collected 307 pieces of meteorite from the blue-ice area (approximately 70.7°S in latitude and 35.6°E in longitude) near the Yamato Mountains in Antarctica. As already reported (NAGATA *et al.*, 1975; YANAI, 1975), special efforts have been continued since 1969 to find and collect meteorite pieces in the blue-ice areas. By the end of 1974, 684 pieces of meteorite-like samples were collected by the Japanese Antarctic Research Expedition teams from a limited area near the Yamato Mountains, now called "Meteorite Ice Field". The total number of meteorite pieces hitherto collected from this "Meteorite Ice Field" amounts to 991.

Up to the present time, only 8 samples have been studied chemically, petrologically and physically in fair detail (*e.g.* NAGATA *et al.*, 1975). All other samples also have been subjected to preliminary petrological examinations. Except three samples, these meteorites are some kinds of stony meteorites, *i.e.* chondrites or achondrites. One exceptional sample is very likely to be a stony-iron meteorite, while the other two can be identified to iron meteorites.

As known well, the statistics of meteorite finds and falls have shown that 35% of all meteorites collected on the earth's surface are iron, and that irons share even 59% of meteorite finds (*e.g.* MASON, 1962). Since it is widely believed that the relatively high abundance of irons and stony-irons (65% in total) as finds is due largely to the easy recognition of them as meteorites and partly to their resistance to weathering, a statistical result with respect to meteorite falls may be considered closer to the true relative abundances of irons, stony-irons and stones in all meteorites which have ever reached the earth's surface. In a statistical result of meteorite falls, irons and stony-irons occupy 6% and 2% respectively of the total falls (MASON, 1962).

Thus, one may face two key questions in regard to the Yamato meteorites; (a) why such a large number of meteorites have gathered within a small limited area in Antarctica? and (b) why almost all of those meteorites, nearly 1,000 in number, are stony meteorites? The simplest possible hypothesis that all the Yamato meteorites are fragments produced by a single large meteorite shower can be rejected because the Yamato meteorite group comprises almost all kinds of meteorites such as enstatite chondrites, bronzite chondrites, carbonaceous chondrites, achondrites, pallasites, hexahedrites and others. However, there remains a possibility that the pieces represent a relatively limited number of falls possibly of the order of 200–300, including several groups of fragments of meteorite showers.

Then, the most plausible hypothesis which can answer the questions (a) and (b) might be a dynamic model of Antarctic ice sheet such as follows:

The meteorites which fell on the Antarctic Continent covered by snow begin to sink slowly into the snow to be covered with further snow, and with the moving ice sheet they are transported toward the sea coast in general. In the course of the general movement of the ice sheet, the uneven topography at the base of the Yamato Mountains may result in a stagnant area as a local horizontal convergence zone, where rapid ablation by the wind will form a blue-ice surface and will expose those meteorites on the blue-ice surface.

At least a horizontally stagnant point of the ice sheet flow is observed in the neighbourhood of a nunatak in the "Meteorite Ice Field" area, where the annual rate of up-well movement of ice amounts to about 5 m/year, and the apparent ablation rate is about 4 m/year, the net ablation rate amounting to about 9 m/year. If the sinking rate is high, the meteorite pieces will not be exposed by the ablation. This gravity separation effect may be the main cause of the observed fact

that only two small pieces (<68 gm in weight) of iron meteorite have been found in the "Meteorite Ice Field", whereas a large number (988 pieces) of stony meteorite including a number of those of much larger mass (>1 kg in weight) have been collected from the same area.

This short note is primarily concerned with metallographic and magnetic studies of one of those rare iron meteorites collected from the "Meteorite Ice Field" in Antarctica.

2. General Description of Yamato-75-105 Meteorite

As shown in Fig. 1, Yamato-75-105 iron meteorite is approximately lenticular in shape (planer-convex) about 2.5 cm in diameter and with a maximum thickness of 1.0 cm. The weight as found was 19.6 gm and the apparent density is 6.868, indicating the presence of internal voids or non-metallic components. The fusion crust of this meteorite surface is generally blue-gray in appearance with small brown flecks visible at low magnification. The sample was sectioned into four pieces for metallographic and magnetic examinations as well as for the storage of the major parts. The cross-section is of course metallic and its hardness is DPH 183, namely rather soft.

Quantitative X-ray fluorescence analysis of the cross-section and the fusion crust indicated the chemical compositions as follows:

	Si	Ni	Ti	Co	P	S	Al	Fe+O
Metal base	0.35	5.65	0.12	0.52	1.0	0.1	0.25	Remainder (wt%)
Fusion crust	2.2	6.4	0.15	0.4	1.5	0.1	5.0	Remainder (wt%)

As hexahedrites are, in general, remarkably uniform in chemical composition which comprises about 93.5% Fe, 5.5% Ni and 0.5% Co, the remainders being P, S, Cr, C, etc. (MASON, 1962), and essentially all kamacite, this iron meteorite can be identified as a hexahedrite. However, since no Neumann band is detectable and a fairly granular structure is dominant due to reheating, this iron meteorite may also be identified as a Ni-poor ataxite which is identical in the chemical and mineralogical compositions to the hexahedrite.

3. Metallographic Properties

Metallographic examination of the cross-section (Fig. 2) revealed that effects of reheating on entry into the earth's atmosphere are evident by the presence of an "ablation" zone about 2 mm in thickness on the flat surface. This zone consists of small recrystallized grains of kamacite surrounding pools of oxide, 10 μm

to 100 μm in diameter (Fig. 3). The dark lines in Fig. 2 are voids partially filled with oxide. The electron microprobe analysis has shown that the oxides filling the black lines are iron-nickel phosphide oxide particles which resulted from melting of $(Fe, Ni)_3P$ particles (melting point $\sim$1000°C) during the reheating process. Fig. 4 is an electron micrograph of the acicular grain structure of the kamacite phase bounded by a void line filled with $(Fe, Ni)_3P$+kamacite eutectic grains (top) and another void line filled with $(Fe, Ni)_3P$ oxide grains (bottom). The aciculer grain structure of kamacite phase is characteristic of rapidly cooled FeNi alloys of this composition (GOLDSTEIN and DOAN, 1972).

Examination at higher magnification in the scanning electron microscope has shown that the phosphide grains are surrounded by an enveloping phase. Qualitative electron microprobe analysis has given the following compositions to the phosphide grains, the envelopes and the matrix:

	Fe	Ni	P	
Phosphide	75	10	15	wt%
Envelope	91	7	2	wt%
Matrix	95	5	—	wt%

Dissolution of phosphides during reheating at about 1,000°C apparently results in the formation of high phosphorus metallic body-center-cubic phase stable at this temperature (DOAN and GOLDSTEIN, 1970). Thus, the precipitated phosphide grains of 75% Fe, 10% Ni and 15% P in composition are enveloped by high-P kamacite of α phase of 91% Fe, 7% Ni and 2% P within kamacite matrix of 95% Fe and 5% Ni in composition.

The major point determined from this preliminary metallographic examination is that the whole sample was heated at least to the melting point of $(Fe, Ni)_3P$, namely about 1,000°C. Further the presence of acicular grain structure in the kamacite phase suggests a rapid cooling rate on the side away from the heat-affected zone. This effect of extensive reheating of the sample makes this sample's exact identification difficult. It was observed further in the electron probe analysis that FeS particles are present together with $(Fe, Ni)_3P$ grains in the oxide patches.

4. Magnetic Properties

Fig. 5 shows the thermomagnetic curves obtained in the condition of the atmospheric pressure $\simeq 10^{-5}$ torr, the external magnetic field=5.85 kOe and the heating and cooling rate=200°C/hour. The magnetization is saturated in this magnetic field: the intensity of saturation magnetization (I_s) at room temperature is 190 emu/gm in the initial state and 185.8 emu/gm after the first heating up to 800°C and in the second-run measurements.

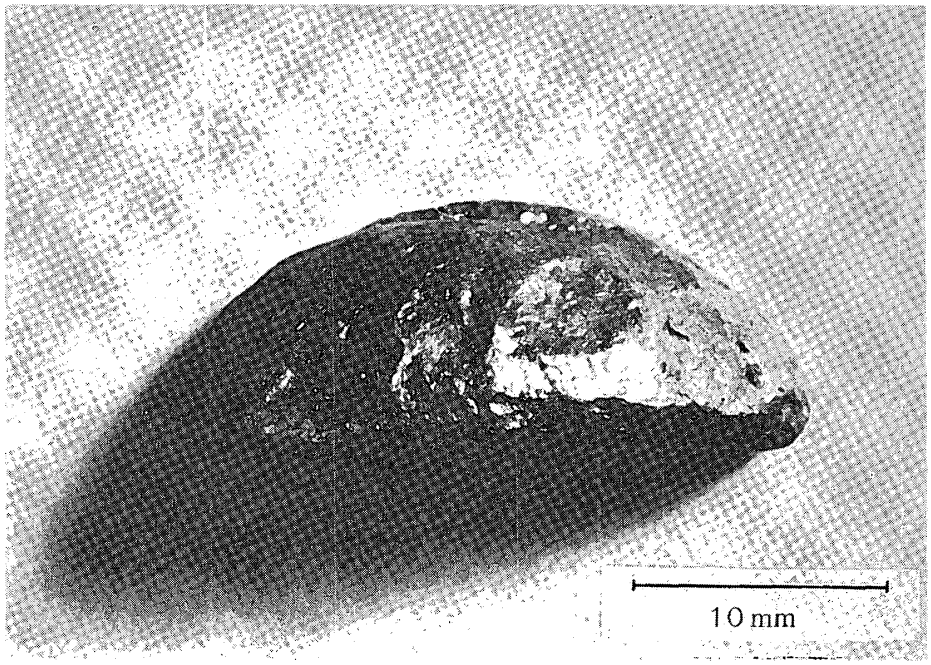

Fig. 1. Yamato-75-105 iron meteorite of a lenticular shape completely covered by a fusion crust layer (Top: concave surface side. Bottom: planer suface side).

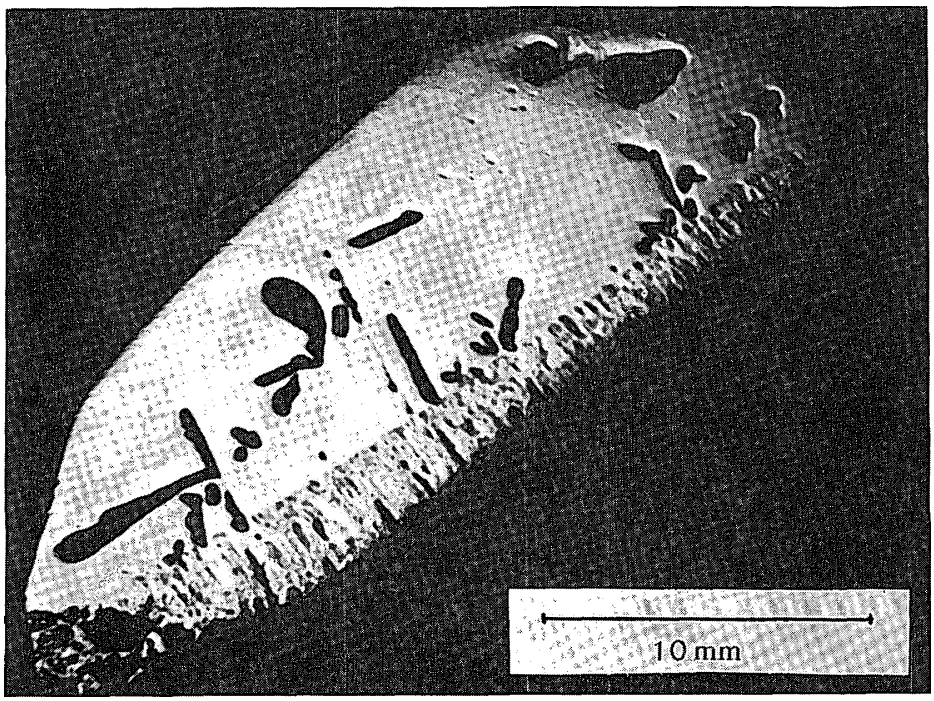

Fig. 2. Cross-section of Yamato-75-105 iron meteorite. The bottom side is an ablation zone. Black lines are melted and oxidized Fe-Ni phosphides.

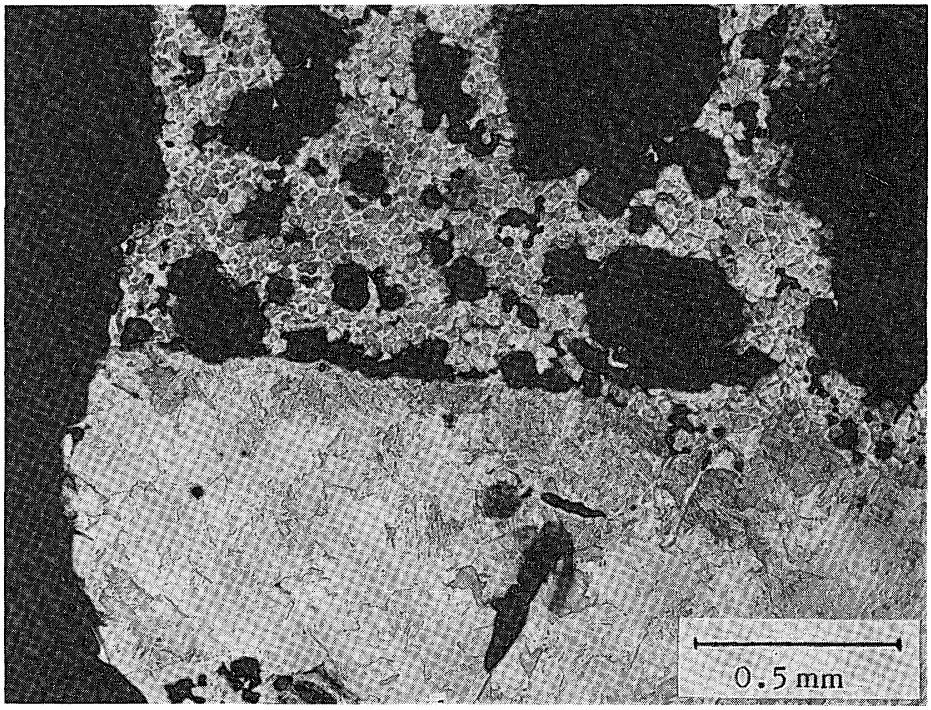

Fig. 3. Recrystallized grains and oxides in the ablation zone (top parts) and acicular grain structure in the kamacite base (bottom parts).

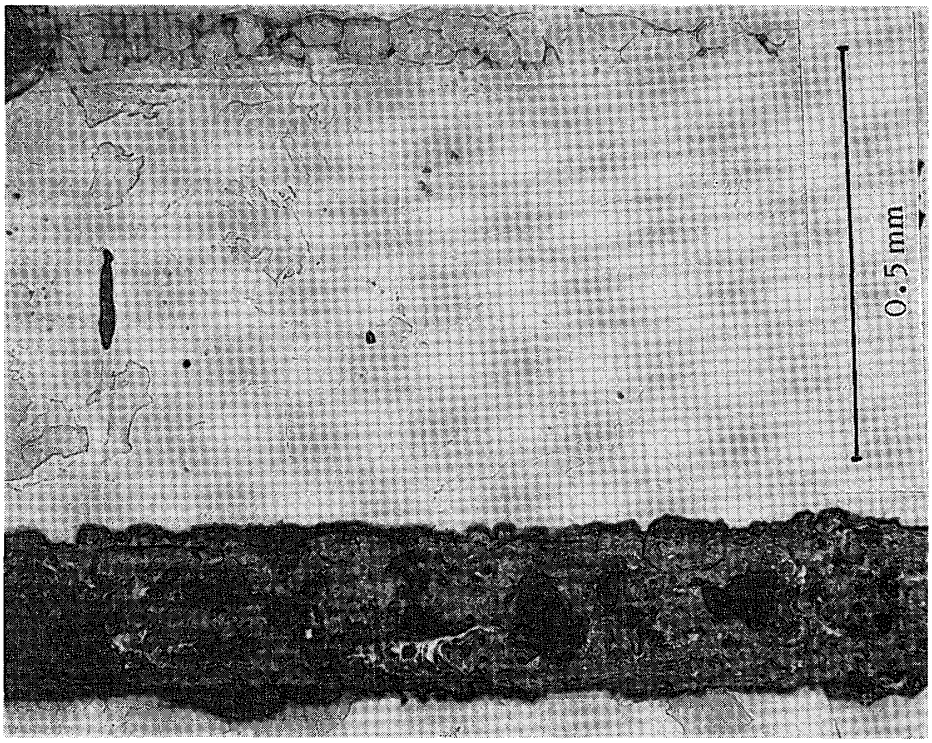

Fig. 4. Void filled with $(Fe, Ni)_3P$+kamacite eutectic (top). Acicular grain structure of 95% Fe, 5% Ni kamacite (middle). Black-coloured void filled with oxides of $(Fe, Ni)_3P$ (bottom).

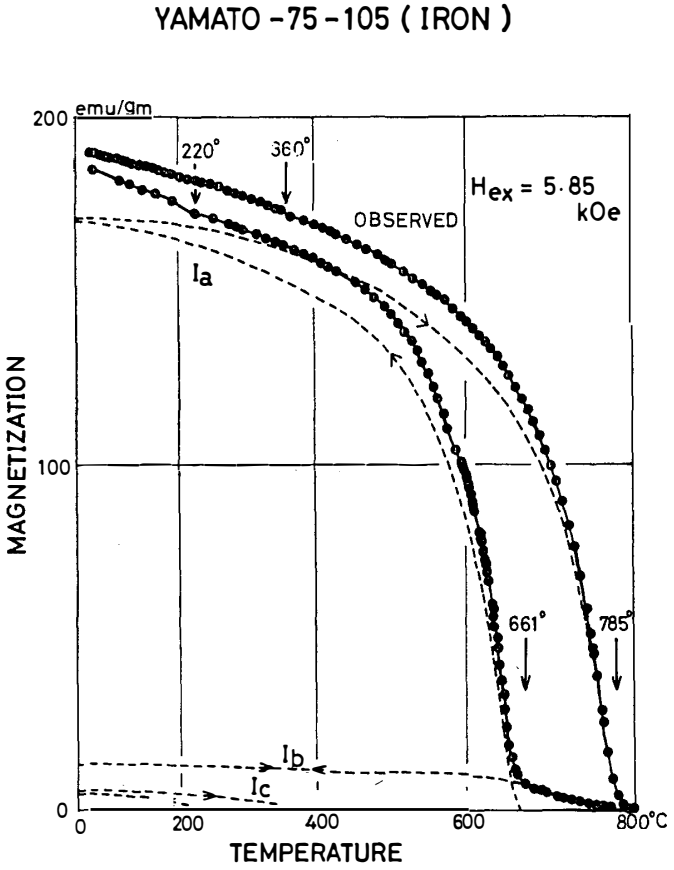

Fig. 5. First-run thermomagnetic curves. Full circles plus full line: observed values. I_a: thermomagnetic curves of 95% Fe, 5% Ni kamacite phase. I_b: thermomagnetic curves of high-P kamacite phase. I_c: thermomagnetic curves of Fe-Ni phosphide phase.

The major magnetic transition temperature is 785°C in the heating curve and 661°C and 770°C in the cooling curve. This thermal irreversibility of magnetization is maintained in the second-run measurements. A comparison of the cooling curve with the heating curve indicates that the major magnetic constituent of this sample comprises (a) a kamacite phase of 5.1% Ni and 0.5% Co of the $\alpha \rightarrow \gamma$ transition temperature in the heating process $\simeq$790°C and the $\gamma \rightarrow \alpha$ transition temperature in the cooling process $\simeq$660°C (BOZORTH, 1951) and (b) a thermally reversible phase of about 770°C in its magnetic transition temperature. The magnetically analyzed composition of kamacite phase (a) is in approximate agreement with the electron-microprobe analysis data of the matrix composition. Then, the second thermally reversible phase (b) is very likely to represent 91% Fe-7% Ni-2% P alloy whose Curie temperature is about 770°C and whose magnetization is thermally reversible.

In the heating curve in Fig. 5, a minor magnetic transition is observed at about 360°C in addition to the major Curie point transition at 785°C. This minor magnetic transition temperature shifts to about 220°C in the cooling curve. The minor transition temperature remains at 220°C in the second-run measurements of the thermomagnetic curve. This minor magnetic phase could be identified to iron-nickel phosphides, $(Fe, Ni)_3P$. The Fe-Ni phosphide having Curie temperature at 360°C can be approximately represented by chemical composition of $(Fe_{2\frac{5}{8}}\ Ni_{\frac{3}{8}})P$ (GAMBINO *et al.*, 1967). Then, the weight contents of Ni and P in this phosphide should be given by 11% Ni and 15% P, which are in approximate agreement with the electron micro-probe analysis data described in the preceding section.

The Fe-Ni phosphide having Curie temperature at 220°C can be approximately represented by chemical composition of $(Fe_{2\frac{1}{8}}\ Ni_{\frac{7}{8}})P$, which has the spontaneous magnetization intensity of about 100 emu/gm at room temperature (GAMBINO *et al.*, 1967). Since the original iron meteorite shows evidence of rapid cooling from about 1,000°C, the originally produced Fe-Ni phosphides in nature are not in the equilibrium state, and the annealing processes of this sample up to 800°C in a laboratory may result in a change of composition of the phosphide towards the equilibrium state. The results of laboratory experiments made by DOAN and GOLDSTEIN (1970) have qualitatively justified the hypothetical process mentioned above.

By comparing the heating curve with the cooling one in the first-run thermomagnetic curves, the magnetization curve obtained by the first-run experiment can approximately be decomposed into three phases, *i.e.*, (a) 5.1% Ni kamacite (containing very little P), (b) high-P kamacite and (c) Fe-Ni phosphide, where the spontaneous magnetizations of each phases at room temperature per unit gram of the sample are given by $I_a=169.4$ emu/gm, $I_b=13.4$ emu/gm and $I_c=7.2$ emu/gm. These magnetically detected phases (a), (b) and (c) reasonably correspond respectively to (a) the kamacite matrix of 95% Fe and 5% Ni in composition, (b) the high-P kamacite envelope of 91% Fe, 7% Ni and 2% P and (c) the phosphide grains of 75% Fe, 10% Ni and 15% P, which have been detected by the electron microprobe analysis. From the observed values of I_b and I_c, the total contents of phosphides and their envelopes are estimated to be about 7% and 5% respectively in weight. These estimated values are approximately consistent with the result of volumetry of these compositions under a microscope, which is about 5% for both compositions.

The second-run thermomagnetic curves also are subjected to a similar analysis. The results are represented by $I_a=166.2$ emu/gm, $I_b=13.4$ emu/gm and $I_c=6.2$ emu/gm, where (c)-phase is interpreted to represent $(Fe_{2\frac{1}{8}}\ Ni_{\frac{7}{8}})P$. The total contents of phosphides and their envelopes in this case are estimated to be about 7% and 6% respectively. These estimated values are in agreement, within the accuracy of experiments, with the corresponding values derived from the first-run experiment. Thus, the main results of magnetic analysis are in reasonably good agreement with

those of metallographic analysis in regard to the main compositions of this iron meteorite sample.

On the other hand, the X-ray fluorescence analysis has shown that the bulk abundances of Ni and P are 5.6% and 1.0% respectively in the metal base. When the weight contents of the phosphides and the envelopes in this sample are denoted by ξ and η respectively, the bulk abundances of Ni and P should be represented by the sum of abundance of each element in the three phases, namely,

$$0.056=0.051\ (1-\xi-\eta)+0.11\xi+0.07\eta, \quad \text{(For Ni)},$$

$$0.010=0.15\xi+0.02\eta, \quad \text{(For P)}.$$

ξ and η thus related to the chemical analysis data amount to about 0.06 and 0.08 respectively. It may be concluded that the results of metallographic and magnetic analyses are consistent, in the order of magnitude, with chemical data also.

5. Natural Remanent Magnetization

The natural remanent magnetization (NRM) of this iron meteorite sample was examined for reference. The measurement of NRM and the AF-demagnetization test were made on the original whole sample. Fig. 6 illustrates the AF-demagnetization characteristics of NRM for both intensity and direction. The NRM is fairly stable against the AF-demagnetization, particularly with respect to its direction. The acquisition of isothermal remanent magnetization (IRM) at room temperature of this sample is empirically expressed as

$$\text{IRM}=(8.0\ H_{ex}+0.05\ H_{ex}^{2})\times 10^{-4}\ \text{emu/gm},$$

where H_{ex} is to be given in unit of Oersted for a range from 0 to 10^2 Oe. Then, the original NRM intensity can be acquired as IRM produced in an external magnetic field of about 56 Oersteds. However, as this iron meteorite sample was transported with utmost care in a non-magnetic dry-case by well-trained scientists from the "Meteorite Ice Field" to the laboratory, the sample could have never been exposed to any magnetic field larger than the geomagnetic field piror to the laboratory experiment. The magnetic viscosity of this sample also has been examined for various different external magnetic fields, where the viscous magnetization acquired in a magnetic field of H during t in time is approximately represented by $bH \log t$. The viscous magnetization of this sample is very small, the coefficient (b) being much smaller than 2×10^{-5} emu/gm, Oe, log (sec). It may thus be concluded that the observed NRM of this sample cannot be attributed to IRM or to the viscous remanent magnetization (VRM) acquired in the presence of the geomagnetic field.

In Fig. 6, the AF-demagnetization curve of IRM whose intensity is nearly the same as that of the observed NRM is shown for comparison. It is obvious in the figure that the stability of NRM is much higher than that of IRM of the same

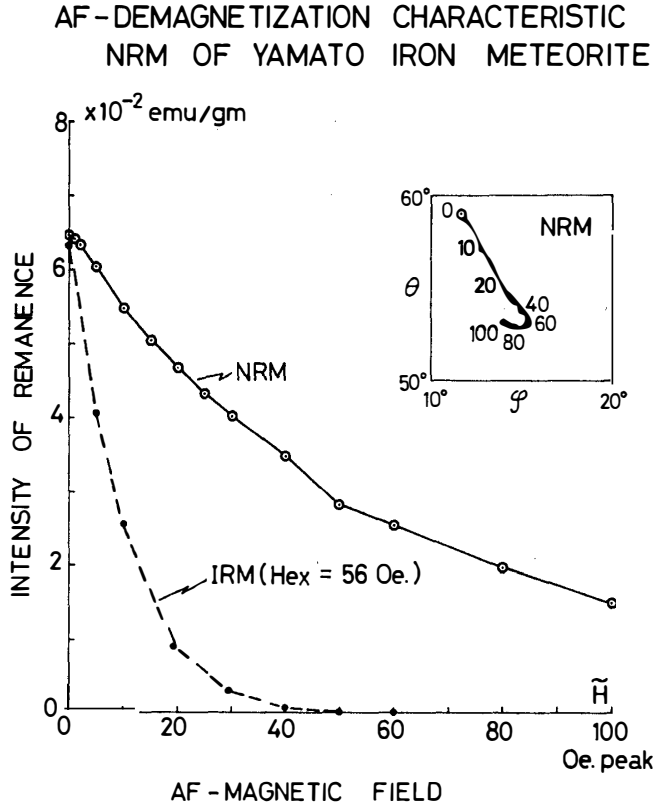

Fig. 6. AF-demagnetization curves of NRM and IRM, the intensity of which is the same as that of NRM. Curve in a rectangular section represents changes in the direction of NRM in the course of AF-demagnetization from 0 to 100 Oe peak.

intensity against the AF-dimagnetization test. This experimental result may suggest that the observed NRM of this iron meteorite was probably acquired as the thermoremanent magnetization (TRM) in the geomagnetic field at the time when the meteorite entered into the earth's atmosphere where a heating up to about 1,000°C and a rapid cooling associated with the formation of Fe-Ni phosphide grains and the enveloping high-P ferrites took place. It seems not easy, however, to exactly reproduce the acquisition process of TRM in laboratory experiments because of a difficulty in producing the initial state of magnetic phase of this meteorite before entering into the earth's atmosphere.

6. Concluding Remarks

This is a preliminary report on chemical, metallographic and magnetic properties of Yamato-75-105 iron meteorite. Further metallurgical studies in detail

are highly necessary to determine a more exact thermal history of this meteorite sample. For example, no studies have yet been made on metal oxide grains which fill a number of void lines. Likewise, consideration of possible similarities between this iron meteorite and the North Chilean hexahedrites (WASSON and GOLDSTEIN, 1968) will require detailed analysis of the Ga, Ge, Ir contents.

Nevertheless, the present study based mostly on metallographic and magnetic data has clearly shown that the structure of this iron meteorite comprises the major parts of kamacite of about 5% Ni, schribersite (Fe-Ni phosphoride of 75% Fe, 10% Ni and 15% P in composition) of 5–6% in weight percentage, and high-P kamacite of α-phase (91% Fe, 7% Ni and 2% P in composition) of 5–6%. Results of chemical analysis by the X-ray fluorescence technique also are approximately consistent with this conclusion. The formation of eutectic region of schribersite and kamacites in this sample indicates that this specimen was reheated up to about 1,000°C. An ablation zone about 2 mm in thickness on the flat surface of this sample is attributable to effects of reheating on entry into the earth's atmosphere.

The presence of acicular grain structures in the matrix of 5% Ni-kamacite indicates a rapid cooling rate from the high temperature. As an extensive reheating of this sample on entry into the earth's atmosphere is evident, the effect of reheating makes classification of this iron meteorite very difficult, but from its chemical composition it appears to be a reheated hexahedrite, *i.e.*, a Ni-poor ataxite. A reheating effect would be the cause of the observed fairly stable natural remanent magnetization of this meteorite.

Upon concluding the report, the authors wish to express their thanks to M. MATSUMOTO who was the leader of the 1975 Yamato Mountains field party for his careful field work which discovered this iron meteorite in the "Meteorite Ice Field" of Antarctica. The authors are indebted also to W. GUNDAKER and C. E. SPANGLER for the electron probe and metallographic examination.

References

BOZORTH, R. M. (1951): Ferromagnetism, Princeton, N. J., D. van Nostrand, 968 p.

DOAN, A. S., Jr. and GOLDSTEIN, J. I. (1970): The ternary phase diagram, Fe-Ni-P. Metallurg. Trans., **1**, 1759–1764.

GAMBINO, R. J., MCGUIRE, T. R. and NAKAMURA, Y. (1967): Magnetic properties of the iron-group metal phosphides. J. Appl. Phys., **38**(3), 1253–1255.

GOLDSTEIN, J. I. and DOAN, A. S., Jr. (1972): The effect of phosphorus on the formation of the Widmannstäthen pattern in iron meteorites. Geochim. Cosmochim. Acta, **66**, 51–69.

MASON, B. (1962): Meteorites, New York, John Wiley, 1–274.

NAGATA, T. (ed.) (1975): Yamato meteorites collected in Antarctica in 1969. Mem. Natl Inst. Polar Res., Special Issue, No. 5, 1–110.

YANAI, K. (1975): Geology. Report of the 17th Japanese Antarctic Research Expedition. 72–76 (in Japanese).

WASSON, J. T. and GOLDSTEIN, J. I. (1968): The North Chilean hexahedrites: Variations in composition and structure. Geochim. Cosmochim. Acta, **32**, 329–339.

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