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MAGNETIC PROPERTIES OF Ni-RICH IRON METEORITES

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Abstract: 6 Ni-rich ataxites (25.6–35.5 wt% in Ni-content) are magnetically analyzed. These Ni-rich ataxites can be classified into 3 groups on the basis of the structure consisting of the major Fe-Ni phases; *i.e.*, (1) ordinary taenite phase (ferromagnetic and paramagnetic γ-phases) only, (Yamato-791694 and the Lime Creek), (2) γ-phase plus tetrataenite (γ'-phase), (the Santa Catharina), and (3) γ-phase plus γ'-phase plus martensitic Fe-Ni metal (α_2-phase), (the Twin City and the San Cristobal). The Tishomingo Ni-rich ataxite has an anomalous structure, which may belong to either group (2) or group (3).

Taenite lamellae of 2 octahedrites (the Toluca and the Itutinga) are also magnetically analyzed. These taenite lamellae have the structure of group (2).

1. Introduction

Thermomagnetic properties of 15 iron meteorites were systematically analyzed by LOVERING and PARRY (1962), dealing mostly with the magnetic transitions of co-existing ferromagnetic Fe-Ni metal phases. Among the 15 examined iron meteorites, Santa Catharina Ni-rich ataxite exhibits an instability of its main ferromagnetic phase having its apparent Curie point at $(550\pm10°)$ C; namely, the observed thermomagnetic curves are thermally irreversible before and after heating to 620°C, suggesting a break-down of the ferromagnetic phase existing in the pre-heating condition. This observed irreversibility of thermomagnetic curves of the Santa Catharina could not be reasonably well interpreted on the basis of metallographic knowledge on those days (LOVERING and PARRY, 1962).

However, an ordered superlattice structure of 50Fe50Ni (in atomic ratio) taenite has been later identified to the main component of the Santa Catharina with the aid of Mössbauer spectral analysis by DANON *et al.* (1979). The 50Fe50Ni superlattice crystal was artificially produced by the neutron bombardment at 320°C in the presence of a strong magnetic field, and its magnetic properties were studied in detail by NÉEL *et al.* (1964).

Because of the tetragonal structure of a unit cell of this ordered crystal of AuCu type, (a=2.533 Å, c=3.582 Å), the anisotropy constants K_1, and K_2 in an expression of $(K_1 \sin^2\theta + K_2 \sin^4\theta)$ of the anisotropy referred to c-axis are determined as $K_1 = 3.2\times10^6$ ergs/cm^3 and $K_2 = 2.3\times10^6$ ergs/cm^3 respectively. Then the magnetic coercive force of an assembly of random-oriented crystals of 50Fe50Ni superlattice structure metal can be about 5×10^3 Oe at maximum. Therefore, the presence of ordered 50Fe50Ni metal in meteorites should be considered extremely significant and important from the viewpoint of meteorite magnetism.

The presence of the ordered 50Fe50Ni metal of the superlattice structure in various meteorites were optically surveyed and confirmed by CLARKE and SCOTT (1980), and the new natural metallic mineral of 50Fe50Ni in composition has been named tetrataenite. In metallographic discussion, the tetrataenite phase is often termed as γ'-phase of Fe-Ni metal (*e.g.* REUTER *et al.*, 1985). For the sake of simplicity, this term, γ'-phase, will be accepted for tetrataenite in the present report.

As far as the unusual thermomagnetic properties of the Santa Catharina are concerned its general magnetic properties covering various characteristics of magnetic hysteresis and thermomagnetic curves are completely re-examined with a result that the anomalous behaviors of thermomagnetic properties are due to γ'-phase possessing an extremely large magnetic coercivity (NAGATA *et al.*, 1986).

Since the Santa Catharina is a Ni-rich ataxite, the bulk Ni-content in which amounts to 35.3 wt%, and the stoichiometic chemical composition of γ'-phase Fe-Ni metal is given by 48.8 wt% Fe and 51.2 wt% Ni, it appears reasonable to presume that Ni-rich ataxites may have a high probability of forming γ'-phase during the course of their very slow cooling below 400°C in nature. For this reason, basic magnetic properties of Ni-rich ataxites are systematically examined with special attention to any characteristic property representing γ'-phase in the present study. Ni-rich ataxites examined in the present work and their bulk Ni-content in weight are Yamato-791694 (35.5% Ni), the Santa Catharina (35.3% Ni), the Tishomingo (32.5% Ni), the Twin City (30.1% Ni), the Lime Creek (29.5% Ni) and the San Cristobal (25.6% Ni).

In addition to the six Ni-rich ataxites, magnetic properties of taenite lamellae of two octahedrites also are especially examined in the present work, because Mössbauer spectral analyses have shown clear evidence for the presence of γ'-phase in the taenite lamellae of these octahedrites. They are the Toluca and the Itutinga.

2. Metallographic and Chemical Compositions of Ni-rich Ataxites and Taenite Lamellae of Octahedrites

In Table 1, the bulk contents of Ni, Co and P for 6 Ni-rich ataxites and 2 octahedrites, and the phase compositions consisting of kamacite (α), disordered taenite (γ), paramagnetic taenite (γ_p) and tetrataenite (γ') phases revealed by Mössbauer spectral analyses are summarized.

The test specimen for the Mössbauer spectral analyses for each meteorite is not exactly the same as that for the magnetic analyses in the present study. As individual γ'-phase domains are of a small size of 10 μm or less in the order of magnitude (probably because of a short-range ordering mechanism for the γ'-phase formation), and their distribution in ferromagnetic and/or paramagnetic taenite (γ- and/or γ_p-phases) is heterogeneous, the Fe-Ni phase composition values given in Table 1 may indicate a general semi-quantitative feature of the phase composition. The conclusion derived from Table 1 will be that about a half of the total metal is occupied by Fe-Ni γ'-phase in the Santa Catharina and taenite lamellae of the Toluca and the Itutinga, while the

Table 1. Bulk chemical composition and Fe-Ni phase composition of Ni-rich ataxites and taenite lamellae of octahedrite.

Meteorite	Bulk composition			Fe-Ni phase composition			
	Ni	Co	P	α	γ	γ_p	γ'
Ni-rich ataxite		(wt%)			(wt%)		
Yamato-791694	35.5	0.60	0.15	(<2)	(>95)	(~0)	(~0)
Santa Catharina	35.3	0.6	0.2	~0	49		51
Tishomingo	32.5	0.5	—	40 (α_2)	47	13	~0
Twin City	30.1	0.5	0.34	62 (α_2)	30		8
Lime Creek	29.5	1.48	0.19	19	66	15	~0
San Cristobal	25.6	1.0	0.18	56 (α_2)	46		8
Taenite lamella of octahedrite							
Toluca	8.14	0.49	0.16				
(Taenite lamella)				(~0)	(36)	(~0)	(64)
Itutinga	7.2	—	—				
(Taenite lamella)				(~0)	(60)	(~0)	(40)

Remark: $\underbrace{\gamma \quad \gamma_p}$ indicates $(\gamma+\gamma_p)$.

Table 2. Chemical composition of bulk and constitutional mineral phases in Yamato-791694 Ni-rich ataxite.

Component	Chemical composition (wt%)			
	Fe	Ni	Co	P
Bulk		35.50	0.60	0.15
Homogeneous taenite matrix	64.03±0.36	35.48±0.41	0.68±0.02	0.01 ±0.007
Kamacite speck	91.32±0.22	6.82±0.10	1.77±0.05	0.035±0.006
Fe-Ni phosphide	41.79±0.51	43.25±0.70	0.32±0.014	15.81±0.07
Ni-rich taenite speck	58.41±0.13	41.00±0.34	0.41±0.02	0.016±0.011

γ'-phase content in the Twin City and the San Cristoblal is aboust 10% or less and practically no γ'-phase is present in the Lime Creek and the Tishomingo.

Although a Mössbouer spectral analysis is not carried out for Yamato-791694 Ni-rich ataxite, chemical analyses of the bulk composition and homogeneous taenite (γ-phase) matrix, kamacite (α-phase) specks, Ni-rich (γ-phase) specks, and phosphide grains are made with the aid of a high-resolution electron microprobe analysis (NAGATA *et al.*, 1984). Judging from the weight contents of Fe, Ni, Co and P in the bulk composition and the four constituting mineral phases, shown in Table 2, it seems very likely that this Ni-rich ataxite is composed of 90 wt% or more of 35.5% Ni taenite matrix, about 1 wt% of Fe-Ni phosphide, 2 wt% or less in total of 6.8 wt% Ni kamacite specks and 41 wt% Ni taenite specks, and practically no tetrataenite. The Fe-Ni phase composition of Yamato-791694 thus estimated is given in parentheses in Table 1.

From the phase composition data in Table 1, it may be expected that some features of magnetic properties of γ'-phase Fe-Ni metal are clearly exhibited in the Santa Catharina and taenite lamellae of the Toluca and the Itutinga, and somewhat exhibited in the Twin City and the San Cristobal, while no γ'-phase characteristic can be detected in Yamato-791694, the Tishomingo and the Lime Creek.

3. Magnetic Properties of Ni-rich Ataxites

The magnetic hysteresis curves of the Ni-rich ataxites are measured in a magnetic field range between 15 kOe and −15 kOe at room temperature (20–25°C) on their original pre-heating condition and after heating to about 800°C twice for their thermomagnetic experiments. Saturation magnetization (I_S), saturated remanent magnetization (I_R), coercive force (H_C) and remanence coercive force (H_{RC}) are taken as the characteristic parameters of magnetic hysteresis phenomenon for individual test specimens at each stage.

Figure 1 shows an example of magnetic hysteresis curves of a Ni-rich ataxite (the Santa Catharina) before and after the heating procedure. In this case, anomalously large values of H_C and I_R in the original pre-heating stage are largely reduced by the heating procedure and the I_S-value is slightly increased by the heating. In addition to I_S, I_R and H_C determinations from these hysteresis curves, H_{RC} is separately measured before and after the heating.

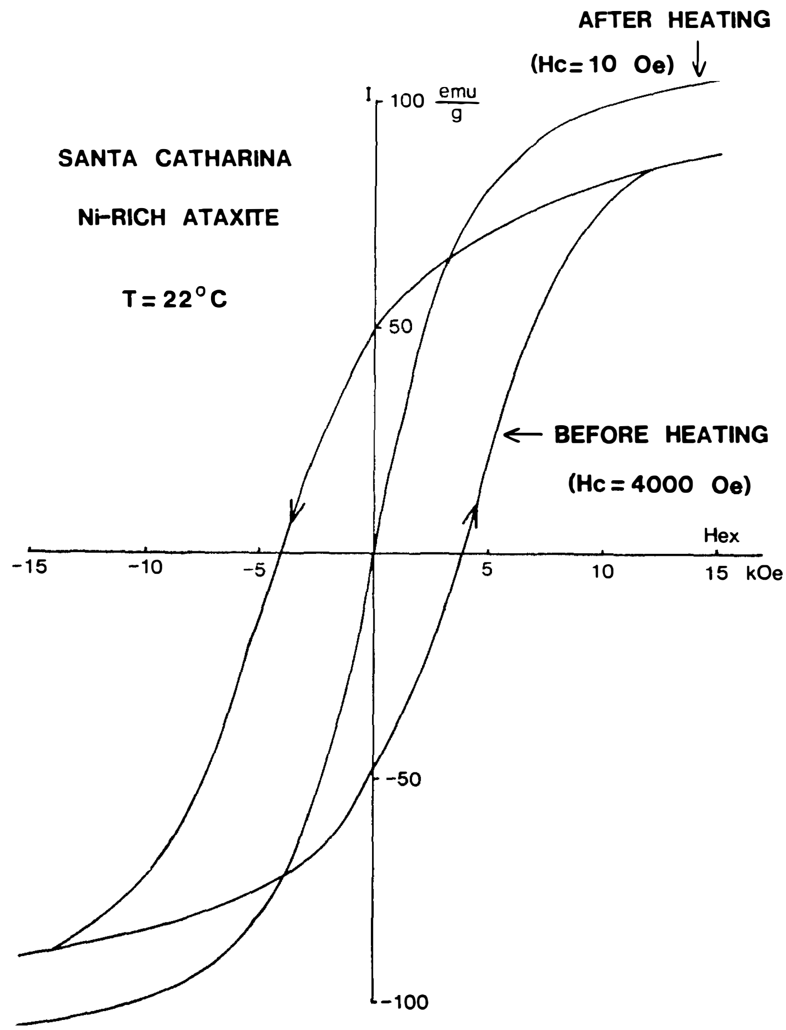

Fig. 1. Magnetic hysteresis curves of the Santa Catharina at room temperature before and after heating twice to 800°C.

The thermomagnetic (TM) curves of individual samples are measured by a vibration magnetometer in $2\times10^{-5}\sim1\times10^{-4}$ Torr atmosphere in a magnetic field of 10 kOe for the purpose of observing the magnetic phase transitions of various different ferromagnetic phases.

3.1. Yamato-791694

The magnetic hysteresis parameters, I_S, I_R, H_C, and H_{RC}, before and after the heat treatment of Yamato-791694 are summarized in Table 3-a, and its first- and second-run TM curves are illustrated in Fig. 2. As the thermomagnetic properties of this Ni-rich ataxite have already been discussed in some detail in a separate paper (NAGATA *et al.*, 1984), magnetic hysteresis characteristics before and after the heating procedure will be briefly summarized in this report.

As shown in Table 3-a, H_C and I_R/I_S in the original pre-heating stage are as small as those of a uniform 35% Ni Fe-Ni alloy, and both H_C and I_R decrease only slightly and H_{RC} considerably decreases by the heat treatment, while α-phase magnetization in the first heating TM curve of $\Theta^*_{\alpha\to\gamma}=740°C$ disappears in the second-rum TM-curve (Fig. 2), suggesting that 6.8% Ni kamacite specks are dissolved into taenite matrix by

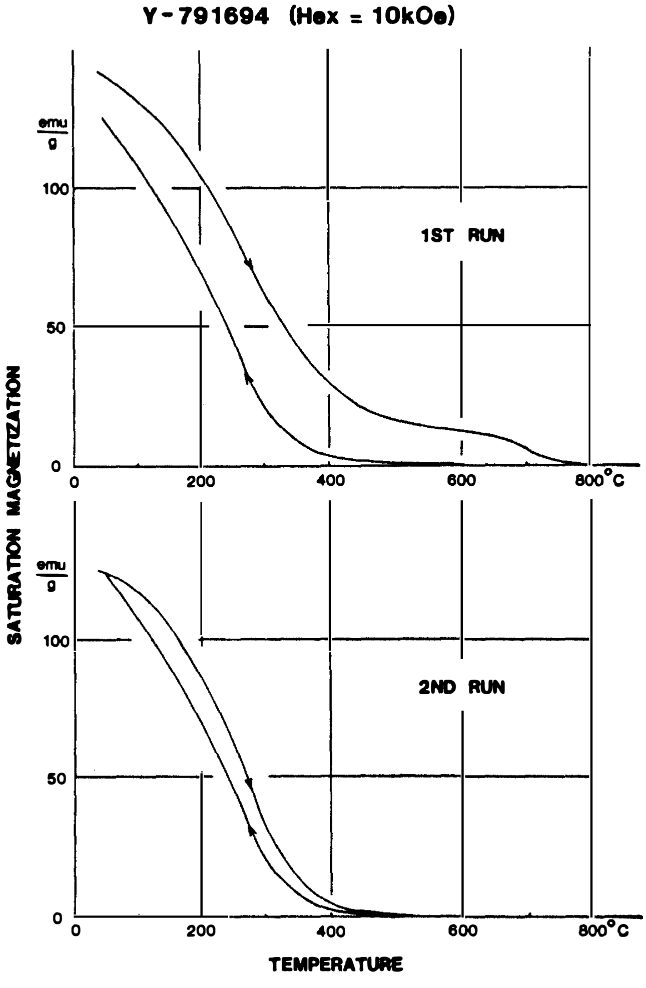

Fig. 2. The first-run and second-run TM curves of Yamato-791694.

Table 3. Magnetic hysteresis parameters of Ni-rich ataxites.

	I_S (emu/g)	I_R (emu/g)	H_C (Oe)	H_{RC} (Oe)
3-a. Y-791694				
1 Original (before heating) (T=22–25°C)	152	0.35	9	220
2 After 2nd heating to 850°C (T=22–25°C)	134	0.20	5	30
3-b. Santa Catharina				
① Original (before heating) (T=25°C)	81	42.5	2800	4060
② After subsequent cooling to −269°C (T=−269°C)	88	51.0	3950	5200
③ After 2nd heating to 800°C (T=25°C)	105	0.225	9.5	335
④ After subsequent cooling to −269°C (T=−269°C)	151	0.35	14	250
3-c-1. Tishomingo No. 1				
1 Original (before heating) (T=22–25°C)	143	1.0	22	165
2 After 2nd heating to 780°C (T=22–25°C)	96	0.15	3.0	66
3-c-2. Tishomingo No. 2				
① Original (before heating) (T=27°C)	138	0.80	19	330
② After subsequent cooling to −269°C (T=−269°C)	171	1.1	24	300
③ After 2nd heating to 750°C and subsequent cooling to −269°C (T=24°C)	175	0.8	18	330
3-d-1. Twin City No. 1				
1 Original (before heating) (T=22–25°C)	85	42.5	760	1030
2 After 2nd heating to 810°C (T=22–25°C)	85	0.20	1.5	30
3-d-2. Twin City No. 2				
① Original (before heating) (T=24°C)	83	15.4	610	1240
② After subsequent cooling to −269°C (T=−269°C)	92	45.0	2400	3500
③ After 2nd heating to 850°C and subsequent cooling to −269°C (T=−269°C)	187	1.2	28	240
④ After 3rd heating to 700°C (T=30°C)	78	0.10	2.5	13
⑤ After 3rd heating to 700°C and subsequent cooling to −269°C (T=29°C)	176	0.65	16.5	275
3-e-1. Lime Creek No. 1				
1 Original (before heating) (T=22–25°C)	114	2.4	20	120
2 After 2nd heating to −269°C (T=22–25°C)	125	1.25	11.5	150
3-e-2. Lime Creek No. 2				
① Original (before heating) (T=24°C)	114	0.4	8	115
② After subsequent cooling to −269°C (T=−269°C)	134	1.8	32	190
③ After 2nd heating to 800°C and subsequent cooling to −269°C (T=−269°C)	154	1.7	25	240
④ After subsequent heating to 24°C (T=24°C)	132	0.65	15	270
3-f-1. San Cristobal No. 1				
1 Original (before heating) (T=22–25°C)	105	6.1	185	3100
2 After 2nd heating to 800°C (T=22–25°C)	93	1.2	24	160
3-f-2. San Cristobal No. 2				
① Original (before heating) (T=24°C)	109	9.3	420	4900
② After subsequent cooling to −269°C (T=−269°C)	119	14.7	795	7210
③ After heating to 790°C and subsequent cooling to −269°C (T=−269°C)	203	1.65	36	260
④ After 2nd heating to 780°C and subsequent cooling to −269°C (T=24°C)	193	1.35	34	285

the heat treatment. The observed considerable dercrease of H_{RC} caused by the heating can be interpreted as due to a disappearance of the effect of a high magnetic coercivity caused by the shape anisotropy of kamacite specks upon the bulk value of H_{RC}.

Generally speaking, however, no remarkable alteration takes place by the heat treatment except the considerable decrease of H_{RC}. The main ferromagnetic phase before and after the heating of Yamato-791694 is γ-phase Fe-Ni metal of about 35 wt% Ni content on average.

3.2. Santa Catharina

The magnetic hysteresis characteristic parameters before and after heating twice to 790°C and TM curves for the first- and second-runs are shown in Table 3-b and Fig. 3 respectively. It is obvious in Table 3-b that I_R, H_C and H_{RC} are markedly reduced by the heating procedure, ratios of the post-heating values to the original pre-heating values being 1/185, 1/295 and 1/12 respectively for I_R, H_C and H_{RC}. The observed anomalously large values of H_C (2800 Oe) and H_{RC} (4060 Oe) in the original pre-heating condition strongly suggest that the main ferromagnetic component in this Ni-rich ataxite is γ'-phase Fe-Ni metal.

As shown in Fig. 3, on the other hand, TM-curve behaviors of the first-run heating TM curve that the decreasing rate of I_S with increasing temperature is very small so

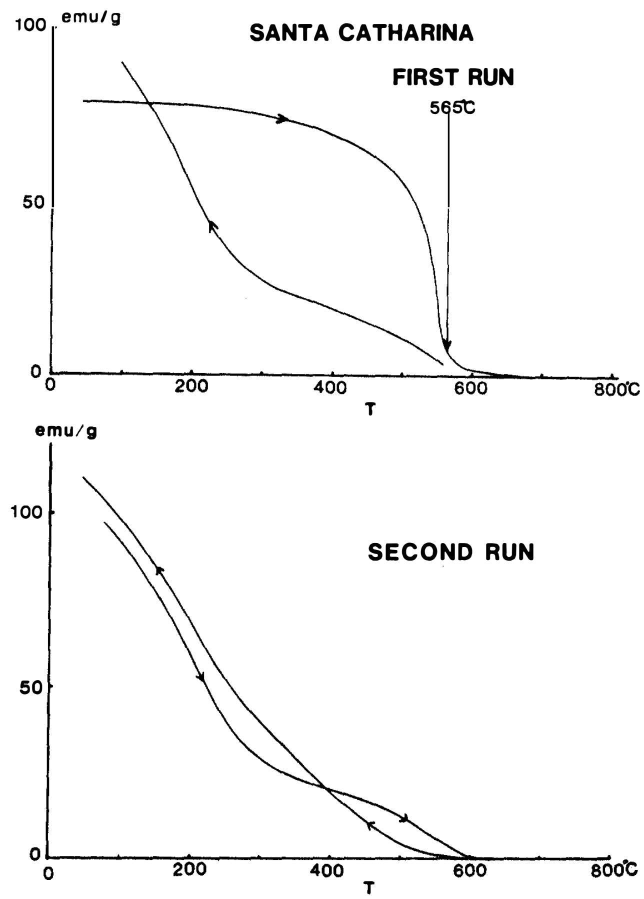

Fig. 3. The first-run and second-run TM curves of the Santa Catharina (Hex=10 kOe).

that the TM curve is flat in a temperature range below about 500°C and then the I_S-value sharply drops down to apparent Curie point at 565°C, are the most characteristic behaviors of TM curve of γ'-phase Fe-Ni metal (*e.g.* NAGATA and FUNAKI, 1982; NAGATA *et al.*, 1986). After the first heating up to 790°C, the TM-curve characteristic of γ'-phase Fe-Ni metal disappears and the first-run cooling and subsequent second-run and third-run TM curves have the TM-curve characteristics of γ-phase Fe-Ni metal phase whose Ni-content is spread over about 30–40 wt% Ni range (NAGATA *et al.*, 1986).

The observed values of I_S, I_R, H_C and H_{RC} after the heating procedure (Table 3-b) are typical values of the hysteresis parameters of γ-phase Fe-Ni of 30–50 wt% Ni. (For reference, the magnetic hysteresis parameters of a synthesized γ-phase alloy of 50% Fe 50% Ni in the present study are I_S=136 emu/g, I_R=0.74 emu/g, H_C=10.5 Oe and H_{RC}=62 Oe at room temperature.) The experimental data of Santa Catharina Ni-rich ataxite given in Table 3-b and in Fig. 3, then, can be put together in a summary that its main ferromagnetic component is γ'-phase Fe-Ni metal in the original state and the γ'-phase is broken down by the heating procedure to γ-phase, Ni-content of which ranges approximately from 30 to 50 wt% Ni.

3.3. *Tishomingo*

Accoding to BUCHWALD (1975), the Tishomingo is a martensitic Ni-rich ataxite, in which the martensitic structure (α_2-phase Fe-Ni metal) is clearly exhibited. Two specimens of this ataxite are magnetically analyzed. The hysteresis parameters at room temperature (25°C) before and after heating twice to 770°C and the first-run and second-run TM curves of Specimen No. 1 are shown in Table 3-c-1 and Fig. 4 respectively.

As expected on the basis of Mössbauer spectral data, no anomalously large values of I_R/I_S, H_C and H_{RC} representing the presence of γ'-phase are observed in Table 3-c-1. The TM curves in Fig. 4 indicate that the first-run TM curve is characterized by a sharp magnetic transition at 570°C and another transition at 390°C, but the subsequent TM curves appear to represent γ-phase magnetizations having Curie point in a temperature range of 200–250°C, which corresponds to γ-phase Fe-Ni metal of 30–31 wt% Ni. No martensitic transformation is observed in the TM curves for a temperature range between 25 and 770°C, as shown in Fig. 4. The Tishomingo No. 2 sample, therefore, is thermomagnetically analyzed for a temperature range between the liquid He temperature (−269°C) and 750°C. Table 3-c-2 shows the hysteresis parameters at room temperature on the original state ①, at −269°C after cooling down ②, at room temperature (24°C) after heating twice to 750°C, then second cooling to −269°C and returning to the room temperature ③.

In the case of Tishomingo No. 2 sample, general features of its TM curves in a temperature range between 0 and 750°C are approximately same as those of No. 1 sample shown in Fig. 4. In the cooling TM curve below 0°C, I_S value increases with decreasing tempreature from 0 to −250°C by about 40 emu/g, but no characteristic sharp martensitic transformation is observed.

In the present study, it is difficult to reasonably interpret both compositional and magnetic properties. A possible provisional summary would be that the Tishomingo is an assembly of α_2-phase, γ-phase and γ_p-phase, containing no γ'-phase at the original

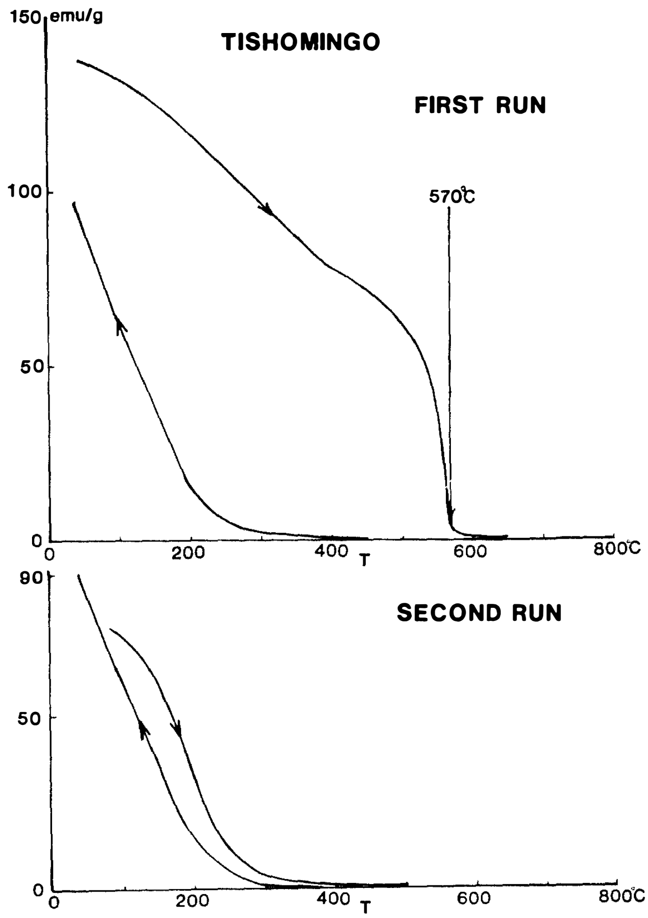

Fig. 4. The first-run and second-run TM curves of the Tishomingo (Hex=10 kOe).

sate, and by heating to about 750°C, all the Fe-Ni metal phases are nearly homogenized to form γ-phases of 30–35 wt% Ni.

3.4. *Twin City*

Accoding to BUCHWALD (1975), the Twin City is an anomalous Ni-rich ataxite, because it contains a significant amount of α-spindles, just as in the case of the Santa Catharina. Results of the present Mössbauer spectral analysis (Table 1) show that this Ni-rich ataxite contains γ'-phase of about 8% in addition to γ_P-phase and α- and/or α_2-phase.

Two specimens of the Twin City are magnetically analyzed. The magnetic hysteresis parameters before and after heating twice to 810°C and the first-run and second-run TM curves for a temperature range between room temperature and 810°C of sample No. 1 are shown in Table 3-d-1 and Fig. 5 respectively.

As clearly shown in Table 3-d-1, I_R, H_C and H_{RC} of the Twin City in the original state are anomalously large, where $I_R/I_S \simeq 1/2$ and $H_{RC}/H_C \simeq 1.35$, and I_R, H_C and H_{RC} after the heating procedure are extraordinarily reduced, the post-heating values of I_R, H_C and H_{RC} becoming 1/212, 1/507 and 1/34 respectively of their original pre-heating values.

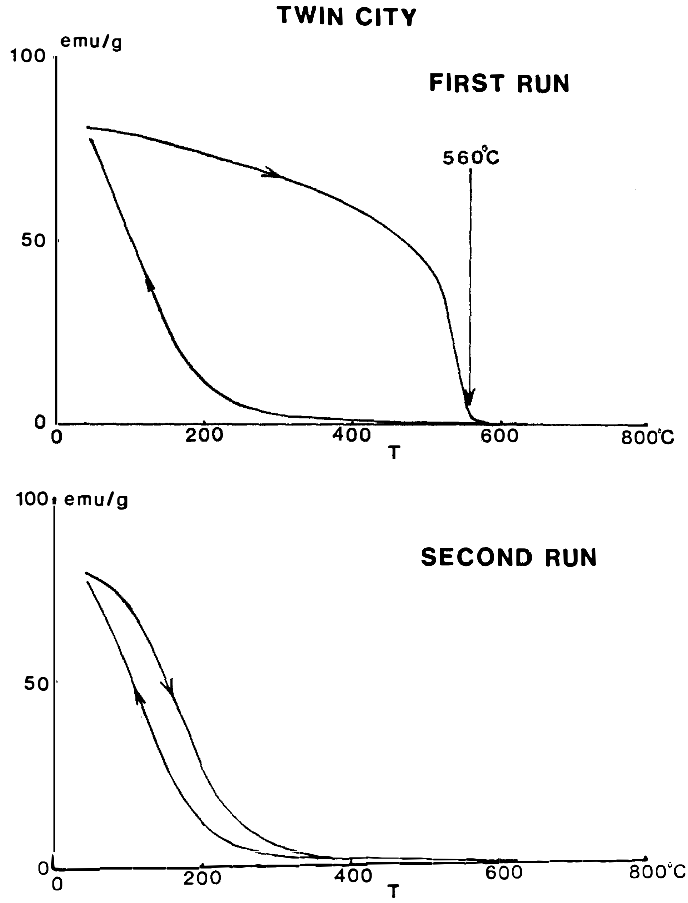

Fig. 5. The first-run and second-run TM curves of the Twin City, Sample No. 1 (Hex=10 kOe).

TM curves in Fig. 5 are closely similar to those of the Santa Catharina (Fig. 3). The first-run heating TM curve is flat in a temperature range below about 500°C and then sharply drops down to apparent Curie point at 560°C, while the subsequent cooling and heating TM curves can be identified to those of γ-phase of 30–40 % Ni.

As far as the experimental data in Table 3-d-1 and in Fig. 5 are concerned, it appears most likely that the original ferromagnetic component is mostly γ'-phase Fe-Ni metal, and after a break-down of the γ'-phase structure to γ-phase by heating, its Ni-content range is broadened by aggregating and mixing with γ_p-phase.

As for Twin City No. 2 sample, the thermomagnetic characteristics are analyzed for temperature range between liquid He temperature and 850°C. Table 3-d-2 summarizes the hysteresis parameters observed at room temperature (24°C) for the original state ①, at −269°C after first cooling, ②, at −269°C after second heating to 850°C and subsequent second cooling, ③, at room temperature (30°C) after third heating to 700°C, ④, and at 29°C after further cooling to −269°C and then returning to the room temperature, ⑤.

Figure 6 shows thermomagnetic cycles of (the second heating process from 30 to 850°C (IIh))→(the second cooling process from 850°C to −269°C (IIc))→(the third heating process from −269 to 700°C (IIIh)), where the first-run cooling from 850°C is terminated at 30°C and the thermomagnetic cycle moves on the second heating process.

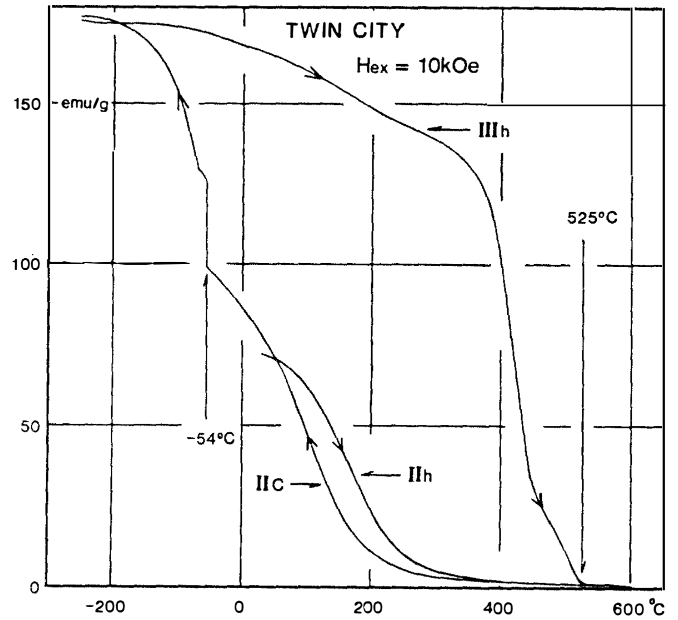

Fig. 6. The second-run heating (II_h) from 24°C, second-run cooling (II_c) from 850 to −269°C, and third-run heating (III_h) (from −269 to 600°C) TM curves of the Twin City, Sample No. 2.

General features of TM curves of the first-run and the second-run in a temperature range from 30 to 850°C are essentially same as those of No. 1 sample shown in Fig. 5, and the first-run heating TM curve from −269 to 0°C is smoothly flat, I_S-value decreasing from 92 to 85 emu/g.

As shown in Fig. 6, however, a martensitic transformation takes place in the cooling process from 850 to −269°C; Martensitic transformation starting temperature (M_s) is −54°C, which corresponds to α_2-phase of 31 wt% Ni. Table 3-d-2 and Fig. 6 show that the b.c.c. α_2-phase is maintained in the third-run heating process until it is transformed to paramagnetic γ_p-phase at transition temperature, 525°C. The third-run cooling TM curve from 30 to −269°C and the forth-run heating TM curve from −269 to 29°C are very similar to those of the second-run cooling and the third-run heating respectively, where M_s temperature in the third-run cooling is −63°C.

The observed differences in I_S, I_R, H_C and H_{RC} of stage ⑤ from those of stage ④ can be mostly attributed to an addition of the α_2-phase magnetization to the γ-phase magnetization. Approximately speaking, therefore, $I_S \simeq 100$ and $I_R = 0.55$ emu/g for the α_2-phase magnetization. It is certain, on the other hand, that the observed differences of I_S, I_R, H_C and H_{RC} of stage ④ from those of stage ① in Table 3-d-2 are mostly due to a break-down of γ'-phase to γ-phase by the repeated heatings to 850°C.

Several problems regarding to the observed magnetic properties of the Twin City are not fully clarified in the present study. A significant unsolved problem may be that the content of γ'-phase in the original state estimated in the present magnetic analysis amounts to about a half of the total Fe-Ni metal, because the I_S-value of both No. 1 and No. 2. samples is about 80 emu/g, while the γ'-phase content estimated from the Mössbauer spectral analysis is only 8%.

A possible summary of qualitatively reliable results of the present analysis of the

Twin City may be as follows: The Twin City consists of α_2-, γ'- and γ_p-phases as its main components so that the ferromagnetic component in the original state is only the γ'-phase Fe-Ni metal.

3.5. *Lime Creek*

The magnetic hysteresis parameters of two specimens of this Ni-rich ataxite before and after heating twice to 800°C are summarized in Tables 3-e-1 and 3-e-2, and TM curves of the first- and second-runs of Sample No. 1 are illustrated in Fig. 7. General features of TM curves of Sample No. 2 are almost same as those of Sample No. 1 in a temperature range between 30 and 800°C.

TM curve characteristics of the Lime Creek are similar to those of Yamato-791694 Ni-rich ataxite. Namely, the largest parts of ferromagnetic component are γ-phase Fe-Ni metals. The magnetic hysteresis parameters of Sample No. 2 in the original stage at room temperature ①, at −269°C after first cooling ②, at −269°C after cooling from 800°C reached in the second heating process ③, and at room temperature elevated from −269°C reached by the second cooling process, ④, are given in Table 3-e-2. The TM curves in a temperature range between 30 and −269°C are flat without any magnetic transformation in each thermomagnetic curve.

No drastic change of the hysteresis parameters is detected between the pre-heating

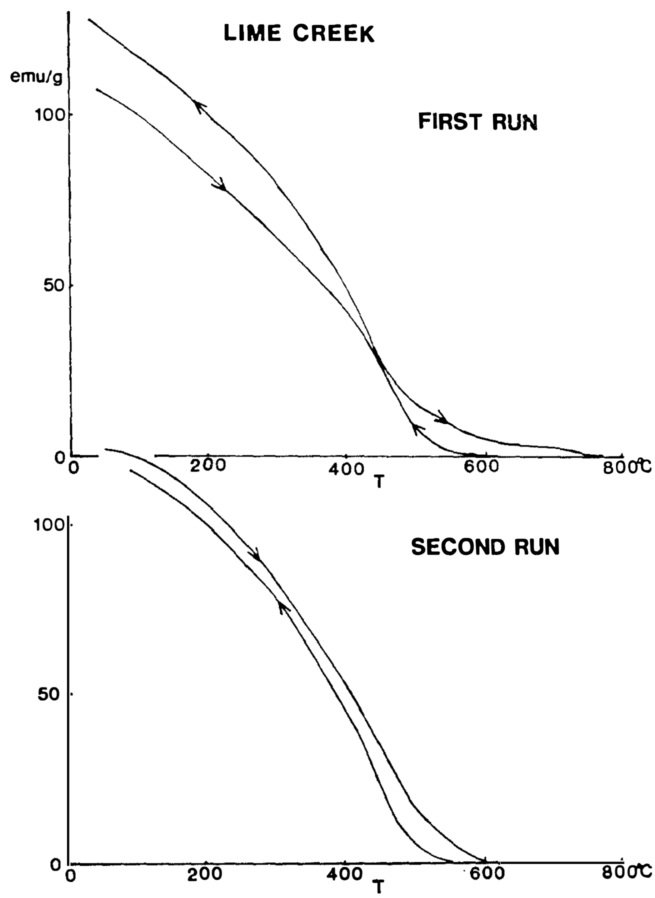

Fig. 7. The first-run and second-run TM curves of the Lime Creek (Hex=10 kOe).

and the post-heating stages, suggesting that γ-phase Fe-Ni metal is nearly stable. However, a small amount of α-phase magnetization detectable in the first-run heating TM curve (Fig. 7) disappears in the subsequent TM curves just as in the case of Yamato-791694 (Fig. 2), suggesting that the α-spindles in the original stage (BUCHWALD, 1975) are dissolved into taenite matrix by the heat treatments.

An unsolved problem in regard to thermomagnetic characteristics of the Lime Creek is concerned with a high value of the observed Curie point of γ-phase around 500°C, which corresponds to almost 50 wt% in Ni-content in the stoichiometric taenite. Ignoring the unsolved point, the main compositional and magnetic properties of the Lime Creek can be summarized in a brief qualitative description that the main ferromagnetic constituent is γ-phase matrix and no γ'-phase is contained.

3.6. San Cristobal

The approximate phase composition of the San Cristobal in Table 1 shows that this Ni-rich ataxite consists of 56% α_2, 36% γ_p and 8% γ'. With respect to the phase composition, therefore, the San Cristobal is somewhat similar to the Twin City.

The magnetic hysteresis parameters of Sample No. 1 of the San Cristobal in the original state and after heating twice to 800°C are summarized in Table 3-f-1, and its TM curves of the first- and second-runs of temperature cycles between 20 and 800°C are shown in Fig. 8.

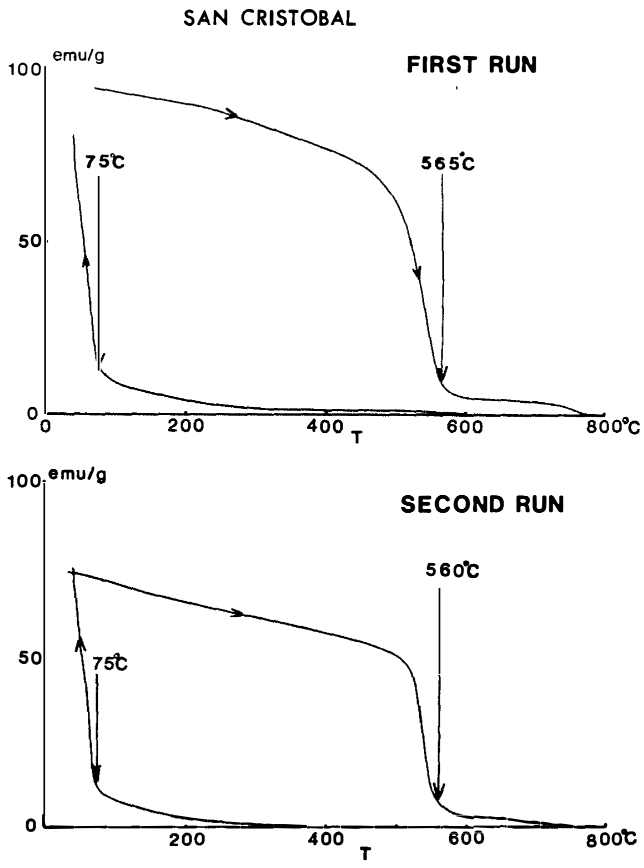

Fig. 8. The first-run and second-run TM curves of the San Cristobal, Sample No. 1 (Hex=10 kOe).

As definitely shown in Table 3-f-1, anomalously large values of H_C and H_{RC} in the original state are largely reduced after heating twice up to 800°C, suggesting a break-down of γ'-phase by the heating procedures. As shown in Fig. 8, on the other hand, it seems likely that the observed characteristic transition at about 565°C of the first-run heating TM-curve is not only due to the transition of γ'-phase but also due to a transformation from α_2-phase (martensitic phase) to γ_p-phase, which is repeated in the second-run TM curve too with a little reduced magnitude. A sharp change of magnetization at 75°C in both cooling TM curves correspondingly indicates a martensitic transformation of α_2-phase of about 29.9 wt% Ni.

Magnetic properties of No. 2 sample are analyzed for a wider temperature range between −269 and 800°C in order to examine the martensitic transformation phenomena in more detail. Table 3-f-2 gives the hysteresis parameters at the original pre-heating stage ①, after first cooling to −269°C ②, after heating to 790°C and subsequent cooling to −269°C ③, and at room temperature after second heating to 780°C and subsequent cooling to −269°C ④. Figure 9 shows TM curves during a process of the second-run heating from −269 to 780°C (IIh process) and a subsequent second-run cooling from 780 to −269°C (IIc process).

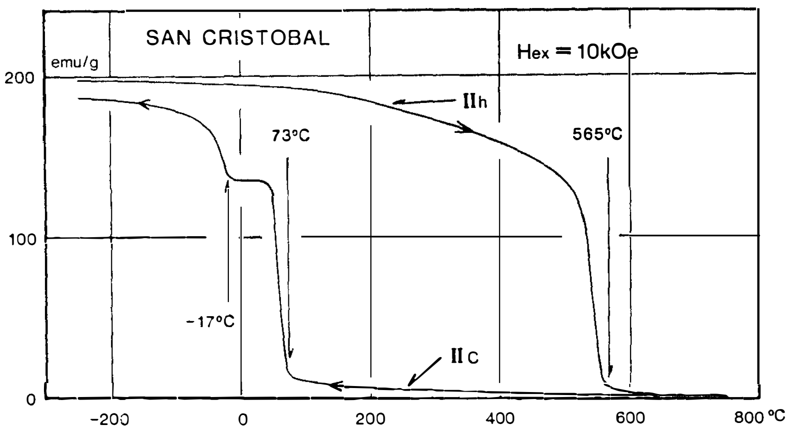

Fig. 9. The second-run heating (II_h) (from −269 to 790°C) and second-run cooling (II_c) (from 790 to −269°C) TM curves of the San Cristobal, Sample No. 2.

It is observed in Fig. 9 that a two-step magnetic transition in the cooling process takes place at M_s=73°C and M_s=−17°C, which correspond to α_2-phases of 29.9 wt% Ni and 26.5 wt% Ni, respectively. The martensitic jumping change of I_S is about 110 enu/g at M_s=73°C and about 50 emu/g at M_s=−17°C so that abundances of 29.9% Ni α_2-phase and 26.5% Ni α_2-phase are estimated to be about 50 and 20% respectively.

A break-down of the originally existing γ'-phase by the first-run heating procedure is indicated by remarkable decreasing changes of I_R, H_C and H_{RC} from the pre-heating stage ② to the post-heating stage ③ in Table 3-f-2 also. In Figs. 8 and 9, a small amount of α-phase of $\Theta^*_{\alpha\to\gamma}$=750°C and $\Theta^*_{\gamma\to\alpha}$=640°C (corresponding to 6% Ni kamacite) is detectable in addition to γ'- and α_2-phases.

Although individual magnetic data thus analyzed appear to reasonably well represent all metal phases revealed by chemical and Mössbauer spectral analyses of the

San Cristobal Ni-rich ataxite, there are still problems in regarding to quantitative representations of individual metal phases, as far as no interaction among these phases is assumed. For example, the bulk Ni-content of this Ni-rich ataxite is 25.4 wt%, while the majorities of metal phase are α_2-phase of 30 and 26.5 wt% Ni and the other phases are 10 wt% or less of γ'-phase of 51 wt% Ni, less than 1 wt% of 6 wt% Ni α-phase and paramagnetic γ-phase. It would be desired that possible metallographic and magnetic interactions among various magnetic phases in iron meteorites are experimentally examined in more detail in the future.

A possible provisional summary of magnetic properties of the San Cristobal at present will be such that this Ni-rich ataxite is composed of α_2-phase of about 70% and the other Fe-Ni metal phases are γ'- and γ_p-phases plus a very small amount of α-phase.

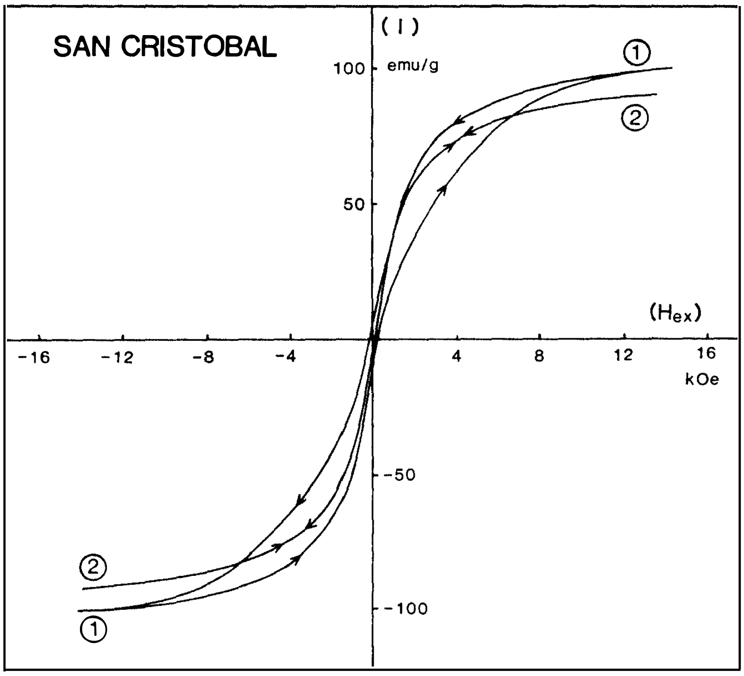

Fig. 10. Magnetic hysteresis curves of the San Cristobal (Sample No. 1) at room temperature before and after heating twice to 800°C.

For an illustrative demonstration, magnetic hysteresis curves of No. 1 sample in the pre-heating original stage ① and in the post-heating stage ② are shown in Fig. 10. The pre-heating hysteresis curve ① is a typical example of a superposition of a low-coercivity ferromagnetic component having small values of I_R and H_C and a smaller amount of a high-coercivity component having extremely larger values of I_R and H_C. The post-heating hysteresis curve ② looks apparently reversible, because both I_R and H_C in this case are much smaller than those of the pre-heating stage ①, as numerically given in Table 3-f-1. It will be certain that the high-coercivity component is the γ'-phase and the low-coercivity component is the α_2-phase.

4. Magnetic Properties of Taenite Lamella of Octahedrites

Since taenite lamellae of Toluca and Itutinga octahedrites have been analyzed by means of Mössbauer spectral analysis method with results that both taenite lamellae contain a large amount of γ'-phase (Table 1), these lamellae also are magnetically analyzed in the same way as for the Ni-rich ataxites.

4.1. Toluca taenite lamella

The magnetic hysteresis parameters of a Toluca taenite lamella before and after heating twice to 790°C are summarized in Table 4-a and its first- and second-run TM curves are shown in Fig. 11. Anomalously large values of H_C and H_{RC} and consider-

Table 4. Magnetic hysteresis parameters of taenite lamellae of octahedrites at room temperature.

	I_S (emu/g)	I_R (emu/g)	H_C (Oe)	H_{RC} (Oe)
4-a. Toluca, taenite lamella				
1 Original (before heating)	111	10.8	960	1950
2 After 2nd heating to 790°C	103	2.65	8.5	33
4-b. Itutinga, taenite lamella				
1 Original (before heating)	74	39.5	2400	3830
2 After 2nd heating to 900°C	99.5	1.7	5	30

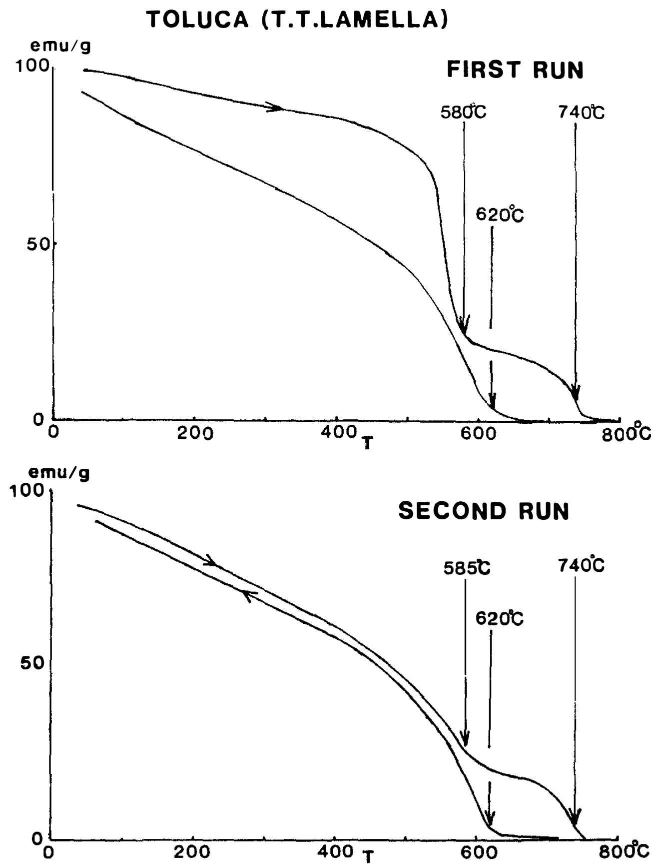

Fig. 11. The first-run and second-run TM curves of taenite lamella of the Toluca octahedrite (Hex=10 kOe).

ably large value of I_R/I_S in the original state and their marked decrease after heating to 790°C certainly indicate that one of main ferromagnetic constituents in this taenite lamella is γ'-phase Fe-Ni metal.

The first-run TM curves in Fig. 11 show that an α-phase component of $\Theta^*_{\alpha\to\gamma}=740$°C and $\Theta^*_{\gamma\to\alpha}=620$°C (corresponding to 6.4 wt% Ni kamacite) is superposed upon the characteristic γ'-phase magnetization. This α-phase component may represent small patches of kamacite which could not be moved out from the taenite lamella surface when the taenite lamella specimen was cut out from the mother octahedrite sample of Widmanstätten structure.

4.2. Itutinga taenite lamella

The hysteresis parameters of Itutinga taenite lamella before and after heating twice to 900°C are summarized in Table 4-b and the first- and second-run TM curves are illustrated in Fig. 12. I_R/I_S, H_C and H_{RC} of the Itutinga taenite lamella are considerably larger than those of the Toluca taenite lamella. Particulary, I_R/I_S amounts to 0.53. The extremely high magnetic coercivity is reduced down to the standard low-coercivity of ordinary γ-phase Fe-Ni metal by heating up to 900°C, the post-heating values of I_R, H_C and H_{RC} becoming 1/23, 1/480 and 1/128 respectively of their pre-heating values.

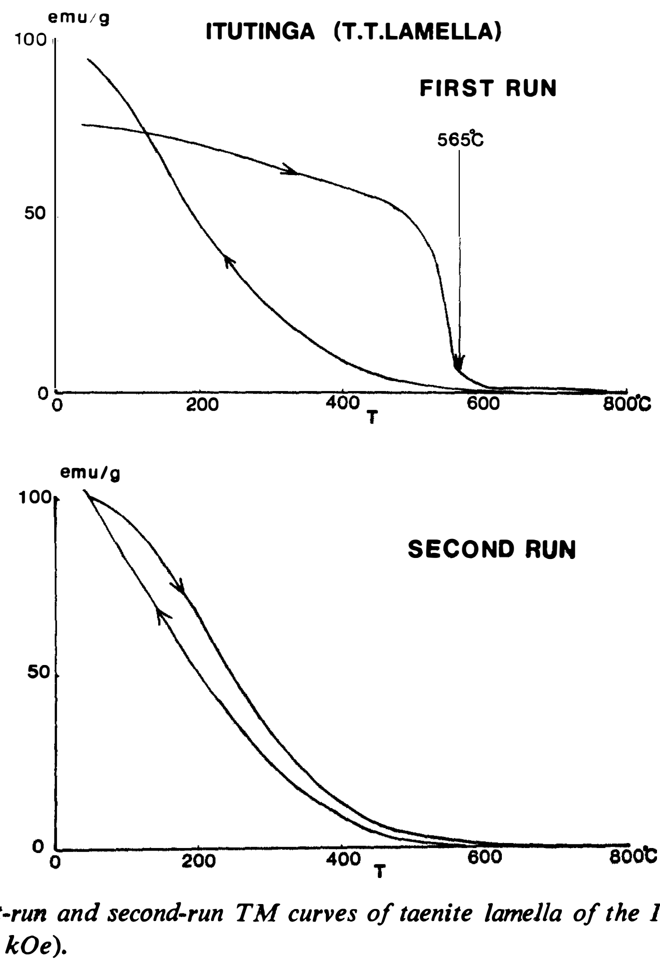

Fig. 12. The first-run and second-run TM curves of taenite lamella of the Itutinga octahedrite (He=10 kOe).

The first-run heating TM curve exhibits the typical standard characteristic for a γ'-phase Fe-Ni metal, and the first-run cooling and subsequent TM curves behave as practically reversible TM curves with temperature for an assembly of γ-phase metals whose Curie points are spread over a temperature range between about 200 and 400°C. These results of magnetic analyses indicate that the main ferromagnetic constituent of this taenite lamella is a γ'-phase Fe-Ni metal, and by a heat treatment up to 900°C, it breaks down to γ-phase Fe-Ni metals of 35–45 wt% in Ni-content, probably due to an amalgamation of the broken-down γ'-phase (51 wt% Ni) with surrounding ferromagnetic and paramagnetic γ-phase components of lower Ni-contents.

Since the first-run TM curves of this sample are approximately identical to those of a mixture of γ'-phase and γ_p-phase Fe-Ni metal (*i.e.* without γ-phase), the γ-phase component of this taenite lamella detected by Mössbauer spectral analysis would be taenites of Ni-content close to 30 wt%, which have only small values of I_S at room temperature.

5. General Characteristics of Magnetic Properties of Ni-rich Ataxites and Taenite Lamellae of Octahedrites

In the present study, 6 Ni-rich ataxites, Ni-contents of which range from 35.5 to 25.6 wt%, are magnetically analyzed. As a matter of course, the content of kamacite (α-phase) is very small or magnetically undetectable in all the six Ni-rich ataxites. Dominant Fe-Ni metal phases are taenite (γ-phase), paramagnetic taenite (γ_p-phase), tetrataenite (γ'-phase) and martensitic Fe-Ni metal (α_2-phase).

Taenite lamellae, which are cut off from two octahedrites having well defined Widmanstätten structure, are composed of γ'-phase and γ- and γ_p-phases.

The presence of γ'-phase is noticeably characterized by anomalously large values of I_R/I_S, H_C and H_{RC} in the original state and a marked depletion of the high magnetic coercivity caused by heating to elevated temperatures beyond about 700°C. Ni-rich ataxites, the Santa Catharina, the Twin City and the San Cristobal, contain a fair amount of γ'-phase Fe-Ni metal. Taenite lamellae of Toluca and Itutinga octahedrites also contain γ'-phase occupying about a half or more of the total Fe-Ni metal. As far as presence of γ'-phase is concerned, therefore, results of the present magnetic analysis well support the results of chemical and Mössbauer spectral analyses given in Table 1.

The presence of α_2-phase is clearly characterized by a sharp martensitic transformation from a paramagnetic γ-phase state to a ferromagnetic α-state at temperature M_s in the cooling process of TM curve. The Twin City and the San Cristobal Ni-rich ataxites contain a fair amount of α_2-phase Fe-Ni metal.

The main ferromagnetic component of Yamato-791694 and Lime Creek Ni-rich ataxites is γ-phase. No evidence for presence of γ'-phase is detected, though their bulk Ni-content is as high as that of the three γ'-containing Ni-rich ataxites. Almost all parts of γ-phase of Yamato-791694 are in ferromagnetic γ-phase state of around 35 wt% in Ni-content, while the γ-phase of the Lime Creek consists of ferromagnetic γ-phase of 40–45 wt% Ni and paramagnetic γ-phase of much less Ni-content.

Magnetic properties of the Tishomingo are anomalous and complicated so that a reasonably self-consistent phase analysis may be difficult from the present experimental data alone. It is ceratain, however, that this Ni-rich ataxite does not contain the

γ'-phase.

Summarizing the magnetic data of the Ni-rich ataxites with reference to their chemical and Mössbauer spectral data, it may be concluded that the Ni-rich ataxite can be classified into three groups; *i.e.* (1) γ-phase ataxite, (2) γ-phase plus γ'-phase ataxite and (3) γ-phase plus γ'-phase plus α_2-phase ataxite. In this classification, the term, γ-phase, covers both ferromagnetic γ-phase and paramagnetic γ_p-phase, because the difference between ferromagnetic γ-phase and γ_p-phase is due to only a difference in Ni-content. The γ-phase ataxite is composed mostly of γ-phase of Ni-content larger than 25 wt%.

The differentiation and subsequent formation of γ-, γ'- and α_2-phases in addition to a smaller amount of α-phase from Fe-Ni melt for Ni-rich iron meteorites ought to be primarily subjected to the thermal history of the meteorites. Since the equilibrium phase diagram of Fe-Ni binary system for a temperature range below about 400°C has not yet been sufficiently established, it does not seem possible at present to understand in detail the formation mechanism of these γ-, γ'- and α_2-phases in meteorites.

The phase structures of the γ-phase ataxites, Yamato-791694 and the Lime Creek, are relatively simple. They consist of γ-phase and α-phase together with several minor constituents such as FeS and (Fe, Ni) P. However, the major constituents of a γ- plus γ'-phase ataxite (the Santa Catharina) are γ'-phase of 51 wt% Ni and γ-phase (including γ_p-phase). As the bulk Ni-content is 35.3 wt% and the share of γ'-phase is about a half for this ataxite, the average Ni-content of the γ-phase is estimated to be about 20 wt%. Then, a certain reasonable mechanism for a differentiation of 35.3 wt% Fe-Ni melt into γ'-phase and γ-phase of 20 wt% Ni on average will have to be considered. This is still an unsolved problem.

The structure of γ- plus γ'- plus α_2-phase ataxites (the Twin City and the San Cristobal) would be more complicated and therefore more difficult for interpretation. The Ni-content of α_2-phase is 31 wt% in the Twin City and two α_2 phases of 26.5 and 30 wt% Ni co-exist in the San Cristobal. The α_2-phases are believed to be formed by a diffusionless transformation mechanism caused by relatively fast cooling through M_S-temperature from a γ-phase having the estimated Ni-content. In addition to such an α_2-phase component, a γ'-phase of a fair amount co-exists together with the ordinary γ-phase in these ataxites. It might be presumed therefore that the γ- plus γ'- plus α_2-phase ataxites have an extremely complicated thermal history during the period since their initial start of formation.

The problem of reasonable interpretation of a formation mechanism for these γ- plus γ'-phase ataxite and γ- plus γ'-plus α_2-phase ataxite could be approached only when a formation mechanism of γ'-phase itself in meteorites is clarified in the future.

In comparison with the phase structure of Ni-rich ataxites, the structure of taenite lamella of octahedrites may be relatively simple. The taenite lamellae of both the Toluca and the Itutinga are mostly composed of γ- and γ'-phases, where the γ'-phase may be concentrated within boundary edge layers in the M-shape profile of Ni-content distribution within a taenite lamella sandwiched by α-phases. Here also necessary conditions for forming the superlattice structure of AuCu type of γ'-phase play the key role in the formation process.

As the magnetic analysis is a powerful method to quantitatively identify and evaluate γ'- and α_2-phases of Fe-Ni metal, as demonstrated in the present study, it is hoped that synthetic studies of same specimens of iron meteorites and metallic components in stony meteorites will be performed with the aid of electron microprobe chemical analysis, X-ray and Mössbauer spectral analyses as well as magnetic analysis in order to more precisely determine their phase structures.

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