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TEMPERATURE DEPENDENCE OF COERCIVITY FOR CHONDRITES: ALLENDE, ALLAN HILLS-769, AND NUEVO MERCURIO

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Abstract: Temperature dependence of the hysteresis parameters (saturation magnetization J_S, saturation remanent magnetization J_R (SIRM), coercive force H_C, remanent coercive force H_{RC} and initial susceptibility X_i) was examined from 30°C to 750°C for Allende (CV3), ALH-769 (L6) and Nuevo Mercurio (H5) chondrites. The NRMs of these chondrites were thermally demagnetized for determination of the NRM blocking (T_B) temperature. The hysteresis parameters were compared with the T_B in order to identify which parameter is the most sensitive to the high coercivity grains. The J_S-T and X_i-T curves showed almost the same transition temperature (Θ_{JS}, Θ_{Xi}), but the Θ_{JS} and Θ_{Xi} were not coincident with the T_B for these chondrites. On the other hand, the main transitions of the Θ_{JR}, Θ_{HC} and Θ_{HRC} in the J_R-T, H_C-T and H_{RC}-T curves were coincident with the T_B. Consequently the temperature dependency of the J_R, H_C and H_{RC} is useful for the determination of the high coercivity grains which carry the stable NRM. The reliable NRMs are carried by tetrataenite in ALH-769, and Nuevo Mercurio, although their main magnetic mineral is kamacite.

1. Introduction

WASILEWSKI (1981) reported the temperature dependent behavior of the magnetic coercivity of Allende (CV3) chondrite. His results elucidated that the NRM (natural remanent magnetization) blocking temperature (T_B) at 320°C in the thermal demagnetization curves was apparent due to a phase transition phenomenon analyzed by the temperature dependence of the coercive force (H_C) and remanent coercive force (H_{RC}). This experimental method seems useful for the estimation of the important carrier minerals of the NRM rather than the Curie point (Θ_{JS}) determined in thermomagnetic (J_S-T) curves.

Sometimes the T_B temperature of meteorites is not coincident with the Θ_{JS}, *e.g.* the NRM intensity decayed 90% between 500° and 530°C but the saturation magnetization decayed 80% just before the phase transition in kamacite with Curie point at 720°C for Farmington (L5) chondrite (STACEY and LOVERING, 1961), the NRM decayed 80% before 550°C but the J_S suddenly decayed at 760°C for Bocaiuva (IAB) iron meteorite (FUNAKI *et al.*, 1988). These disagreements are common for the chondrites. Since the significant NRM should result from magnetic minerals with the high coercivity, the measurement of the temperature dependent change of coercivity is more important than a determination of the Curie point for NRM analysis. If samples include a small amount of high coercive grains in a large amount of the low coercive matrix, identification of the magnetization resulting from the high coercive ones may be difficult in the J_S-T curves. In this study,the magnetic hysteresis properties (saturation magnetization J_S, saturation remanent magnetization J_R (SIRM), H_C, H_{RC} and initial susceptibility X_i) were measured during the heating and cooling procedure for Allende, Allan Hills (ALH)-769 (L6), and Nuevo Mercurio (H5) chondrites in order to find which parameter is more sensitive to the high coercivity grains.

2. Samples and Experiments

Subsamples (about 0.5 g) of fresh samples were obtained from the interior of the Allende, ALH-769, and Nuevo Mercurio. They were ground into less than 0.1 mm fragments. A fragment (about 0.1 g) from the respective samples was placed in a sample holder made of aluminum-oxide ceramic.

The magnetic hysteresis loops were obtained between -1.4 and $+1.4$ T external magnetic field using a vibrating sample magnetometer with computer control. The samples were heated from 30° to 750°C with heating rate 50°C/h, and a cooling rate 100°C/h in 10^{-4} Pa atmospheric pressure. The loops were continuously measured during the experiment; the complete loop requiring 20 minutes. The temperature changed about 16°C for the heating and about 32°C for the cooling in a loop cycle. The hysteresis properties, J_S, J_R, H_C, and X_i values were determined from the loop. The H_{RC} value was independently obtained from the loop. When the H_C value was smaller than 1 mT, the H_{RC} was not measured because of poor precision. Although magnetization in the J_S-T curves superposes ferro (ferri) magnetic and paramagnetic components, the J_S-T curves in this study show only the ferro (ferri) magnetic component; the paramagnetic one being subtracted. In this study, transition points appearing in the J_R-T, H_C-T, H_{RC}-T and X_i-T curves are denoted as Θ_{JR}, Θ_{HC}, Θ_{HRC} and Θ_{Xi} respectively.

The NRM characteristics of 3 chondrites were examined against AF demagnetization to 50 mT and thermal demagnetization from 30° to 630°C. During the thermal demagnetization, the samples were enclosed in glass tubes in the vacuum condition 10^{-4} Pa. Their NRMs were measured by a 3-axis cryogenic magnetometer.

3. Experimental Results

3.1. Allende

The NRM (3.2×10^{-4} Am^2/kg) of Allende was very stable against AF demagnetization up to 50 mT. The result of thermal demagnetization (Fig. 1) indicated that the NRM sharply decays up to 320°C, and subsequently decays gradually to about 1/20 of the initial value at 580°C. These characteristics for the demagnetization were essentially consistent with previous reports.

The J_S-T curve of Allende (Fig. 2a) showed clearly defined large Θ_{JS} at 610°C and several small ones between 80°C and 350°C in the heating curve. However, the determination of the minor Θ_{JS} in the heating curve is difficult, because the minor one is too small for magnetization change. In the cooling curve, large Θ_{JS} at 610°C and small one at 290°C were observed. The $J_s=8.60\times10^{-2}$Am^2/kg of original sample increased to $J_S=17.07\times10^{-2}$Am^2/kg after heating to 750°C due to oxidation of sulfide.

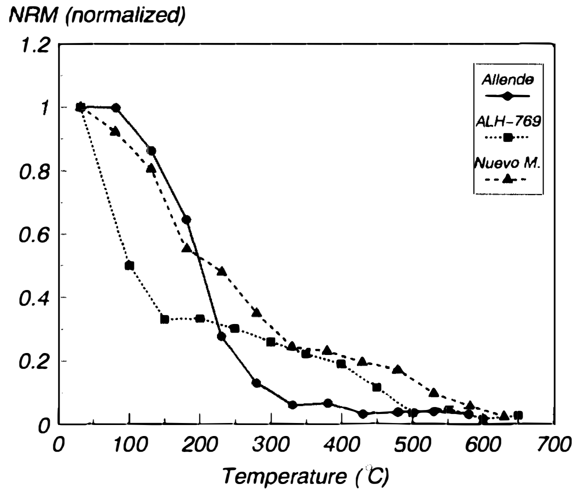

Fig. 1. Thermal demagnetization curves of the NRM intensity for the Allende, ALH-769 and Nuevo Mercurio chondrites.

The J_R-T curve (Fig. 2b) indicated the Θ_{JR} at 320°C and 560°C in the heating curve and at 590°C in the cooling curve. The original $J_R = 18.44 \times 10^{-3}$ Am^2/kg decreased to $J_R = 4.23 \times 10^{-3}$ Am^2/kg at 320°C in the heating curve and changed to $J_R = 10.46 \times 10^{-3}$ Am^2/kg at 30°C after heat treatment.

The H_C-T curve was very similar to the J_R-T one (Fig. 2c) with clearly defined Θ_{HC} at 330° and 560°C, and minor one at 150°C in the heating curve, and the large Θ_{HC} at 590°C in the cooling curve. The original $H_C = 16.8$ mT decreased to 4.7 mT at 330°C and 0.24 mT at 560°C. The H_C value after heating was 5.4 mT at 30°C.

Although the H_{RC}-T curve was noisy, the heating curve is shown in Fig. 2d. The H_{RC} value could not be easily measured at temperature higher than 540°C, because H_C values were less than 1 mT and control was difficult. However, temperature dependency of H_{RC} value can be roughly identified; the original $H_{RC} = 97.9$ mT decreased to 23.1 mT at 320°C and $\Theta_{HRC} < 10$ mT at 530°C with the Θ_{HRC} at 245°, 320° and ~500°C. A hump appeared between 300° and 400°C suggesting chemical alteration during the heat treatment.

The X_i-T curve gradually changed up to 500°C, and then abruptly decayed between 500° and 610°C in the heating curve and abruptly increased between 610° and 500°C in the cooling curve, as shown in Fig. 2e. The Θ_{Xi} was defined at 610°C for the heating and cooling curves associated with small ones at 280°, 360° and 420°C in the heating curve and at 445°C in the cooling curve. The original $X_i = 1.098 \times 10^{-4}$ increased to 1.931×10^{-4} at 30°C after heat treatment.

3.2. ALH-769

The NRM intensity of ALH-769 (1.81×10^{-3} Am^2/kg) steeply decreased down to less than 1/5 of the initial value by AF demagnetization to 6 mT and then often observed zigzag variations appeared. The thermal demagnetization results (Fig. 1) indicated that the NRM decayed steeply from 30° to 150°C and gradually decreased from 150° to 500°C. The NRM higher than 500°C may be insignificant due to small magnetization

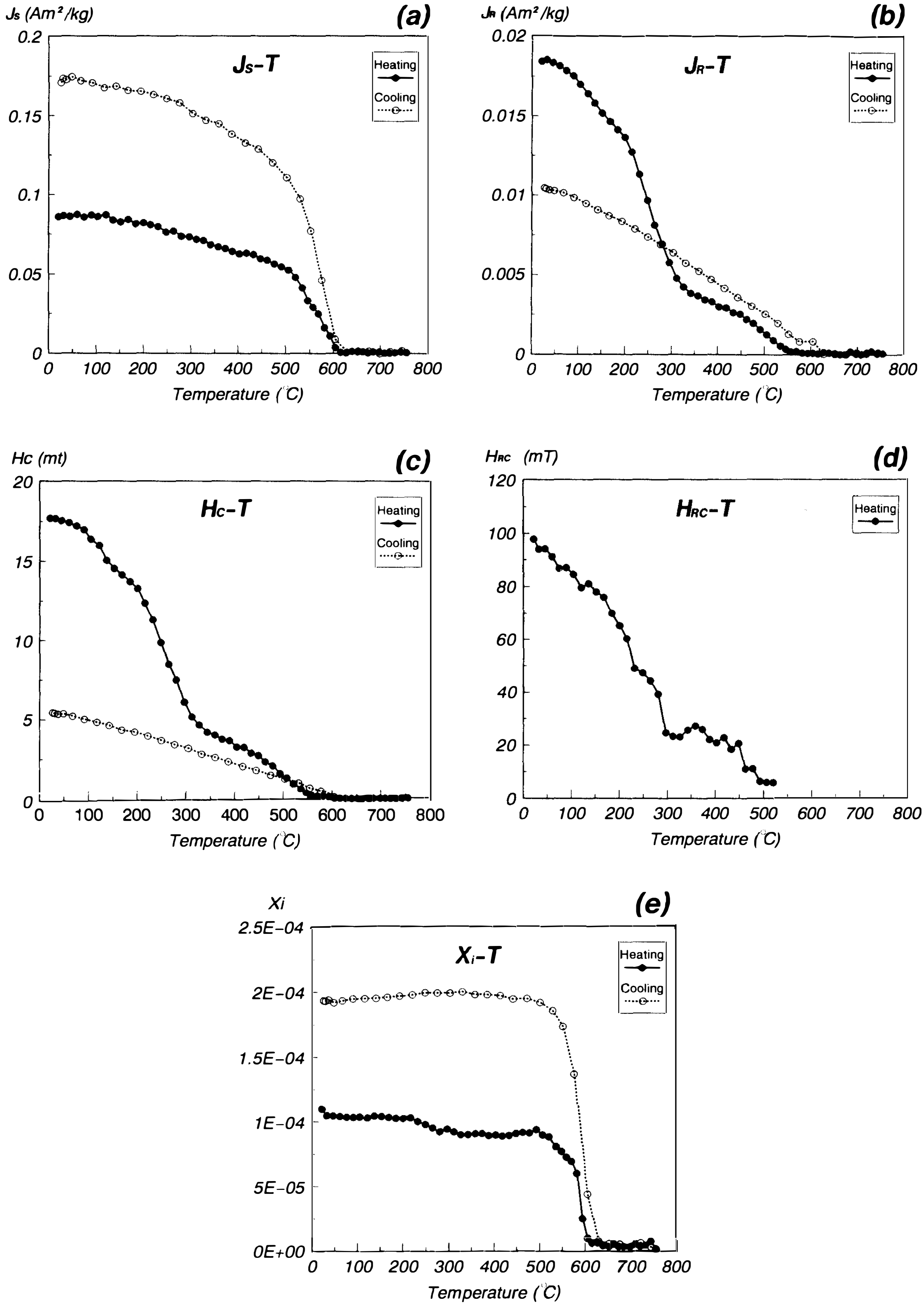

Fig. 2. Temperature dependence of J_S, J_R, H_C, H_{RC} and X_i values for the Allende. (a) J_S-T curve, (b) J_R-T curve, (c) H_C-T curve, (d) H_{RC}-T, (e) X_i-T curve.

and zigzag variation. The direction was relatively stable between 200° and 500°C, but it scattered widely at the both sides of the temperature range.

The J_S-T curve of ALH-769 (Fig. 3a) clearly defined Θ_{JS} at 550° and 745°C and minor one at 500° and 690°C, *etc.* in the heating curve and 670° and 405°C in the cooling curve. The original $J_S = 9.48 \times 10^{-2} Am^2/kg$ increased to $11.37 \times 10^{-2} Am^2/kg$ after heating to 750°C.

The J_R-T curve (Fig. 3b) showed one large Θ_{JR} at 560°C and small one at 640°C in the heating curve, and several small ones in the cooling curve. The original $J_R = 11.43 \times 10^{-3} Am^2/kg$ decreased to only 3% ($3.54 \times 10^{-4} Am^2/kg$) at 560°C and was negligible at 640°C in the heating curve. The value of $J_R = 1.61 \times 10^{-3} Am^2/kg$ appeared at 30°C after heat treatment.

The H_C-T curve (Fig. 3c) was very similar to the J_R-T curve; clearly defined Θ_{HC}

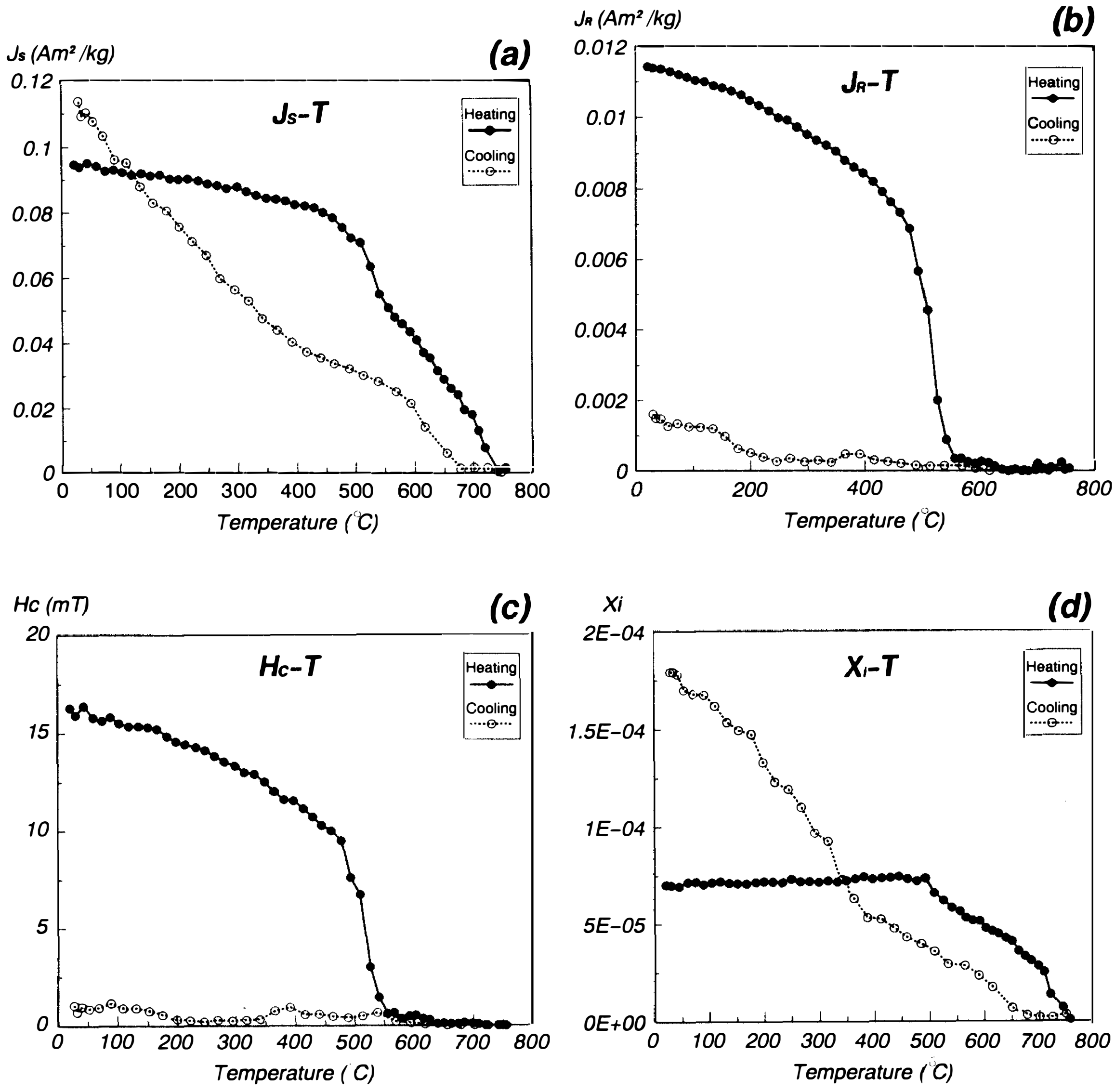

Fig. 3. Temperature dependence of J_S, J_R, H_C, H_{RC} and X_i values for the ALH-769. (a) J_S-T curve, (b) J_R-T curve, (c) H_C-T curve, (d) X_i-T curve.

at 560°C and minor one at 640°C in the heating curve and several unclear ones in the cooling curve were identified. The original $H_C = 16.3$ mT decreased to 3.7% (0.6 mT) at 560°C in the heating curve. In the cooling curve, the H_C value appeared at 560°C and $H_C = 0.86$ mT at 30°C after heat treatment.

The gradually decreasing H_{RC}-T curve was observed and the original $H_{RC} = 122.7$ mT reached an insignificant value at 560°C, although the curve was very noisy. In the cooling curve the value was not measured due to H_C values less than 1 mT.

The X_i-T curve (Fig. 3d) showed almost a flat curve from start to 500°C and then decreased gradually to $\Theta_{Xi} = 755$°C in the heating curve with the small Θ_{Xi} at 570° and 670°C. In the cooling curve, the X_i value appeared from 670°C with the Θ_{Xi} at 670°, 525° and 380°C. The original $X_i = 7.03 \times 10^{-5}$ increased about 2.5 times (1.79×10^{-4}) after heat treatment.

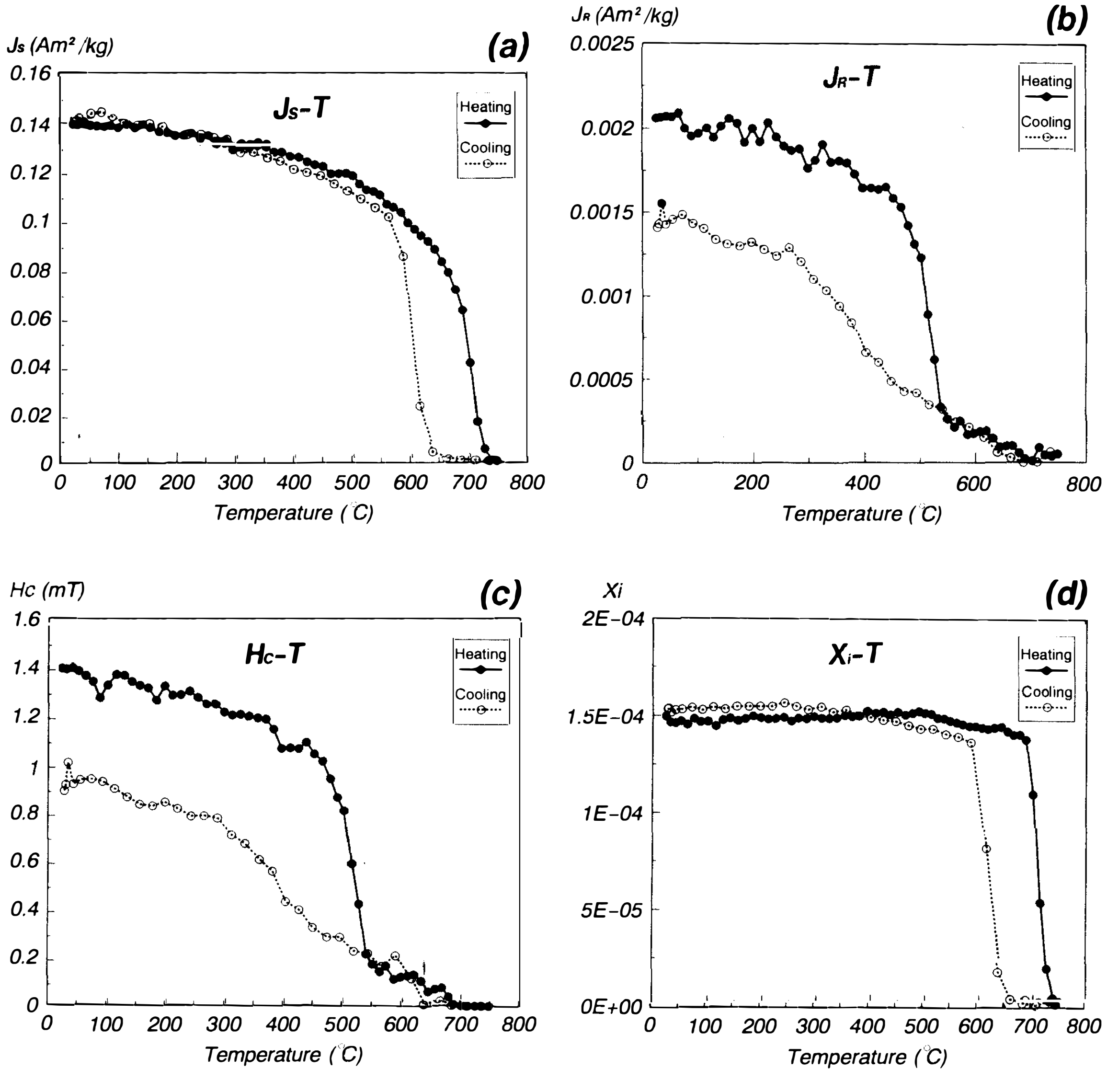

Fig. 4. Temperature dependence of J_S, J_R, H_C, H_{RC} and X_i values for the Nuevo Mercurio. (a) J_S-T curve, (b) J_R-T curve, (c) H_C-T curve, (d) X_i-T curve.

3.3. Nuevo Mercurio

The NRM (1.06×10^{-2} Am^2/kg) of Nuevo Mercurio was very unstable against AF demagnetization. It decayed to 67% at 5 mT, subsequently exhibiting the zigzag pattern up to 50 mT with unstable NRM directions. Against thermal demagnetization, the NRM was more stable than during AF demagntization, with the T_B at 180°, 330° and 530°C, as shown in Fig. 1. Although the NRM direction widely shifted between 30° and 80°C, it was stable from 130° to 630°C.

The J_S-T curve of Nuevo Mercurio (Fig. 4a) showed a clear Θ_{JS} at 745° in the heating curve and clear one at 655° in the cooling curve. The original $J_S=13.95\times10^{-2}$Am^2/kg did not change drastically (14.19×10^{-2}Am^2/kg) after heat treatment.

The J_R-T curve (Fig. 4b) showed a large Θ_{JR} at 565°C, minor one at 700°C and several unclear ones in the heating curve, and at 650° and 385°C in the cooling curve, although the curve showed zigzag variations. The original $J_R=2.05\times10^{-3}$Am^2/kg decreased to about 72% (1.41×10^{-3}Am^2/kg) after heat treatment.

The H_C-T curve (Fig. 4c) was also similar to the J_R-T one not only for transition temperature but also for the similarity of minor variations in J_R and H_C; clearly defined Θ_{HC} at 565°C and 700°C and several unclear ones in the heating curve. In the cooling curve, the H_C was observed from 650°C to 30°C in the cooling curve with Θ_{HC} at 650° and 385°C. The original $H_C=1.41$ mT decreased to 65% (0.91 mT) after heat treatment.

The H_{RC}-T curve could not be measured satisfactorily. However, the H_{RC} was measured at 30°C before and after heat treatments as $H_{RC}=12.8$ mT and 6.7 mT respectively.

The X_i-T curve (Fig. 4d) was almost flat up to 700°C and then abruptly decreased to 745°C in the heating cycle with a clear Θ_{Xi} at 745° and several minor transitions. In the cooling curve, the significant X_i value appeared at 655°C and rapidly increased to 575°C. Several minor Θ_{Xi} were observed in the cooling curve as well. The original $X_i=1.497\times10^{-4}$ changed little (1.534×10^{-4}) after heat treatment.

4. Discussion

The high coercivity minerals are able to carry NRMs of significance for the paleomagnetism of meteorites. Fine magnetic grains (less than about 0.1 μm) having single-domain (SD) and pseudosingle-domain (PSD) characteristics have high coercivity; the larger grains with low coercivity exhibit multi-domain (MD) characteristics. The magnetic minerals with uniaxial magnetocrystalline anisotropy show high coercivity independent of the grain size; tetrataenite (50Fe50Ni ordering phase) which exhibits tetragonal properties of AuCu type, carries high coercivity (WASILEWSKI, 1982; NAGATA and FUNAKI, 1986); hexagonal ferrimagnetic pyrrhotite ($Fe_{1-x}S$) also shows high coercivity. When the tetrataenite is heated to 550°C, it changes into teanite (50Fe50Ni) of low coercivity. Ferrimagnetic pyrrhotite becomes paramagnetic at 320°C.

Usually it is difficult to obtain the Θ_{JS} of high coercivity grains and/or indications of disordering in the J_S-T curves, when the magnetic properties of the grains satisfy the following conditions. (1) If a small amount of the high coercivity material is present in the large amount of MD material, the Θ_{JS} resulting from the high coercivity grains is barely perceptible in the J_S-T curves due to large spontaneous magnetization by the MD grains. (2) If the coercivity changes by disordering during heating, the alteration cannot be detected in the J_S-T curves when the spontaneous magnetization is almost equivalent before and after the alteration. It may be also difficult to estimate the information of the high coercivity grains in the X_i-T curves. The X_i-T curves show characteristics similar to the J_S-T curves, because both curves reflect dominant kamacite with MD structure. The H_C value shows the average coercivity of the sample and the H_{RC} value reflects the high coercivity grains (NAGATA and CARLETON, 1987). The parameter J_R, similarly reflects coercivity, *i.e.*, H_C and H_{RC}. As the reliable NRM is carried by the high coercivity grains, the analyses of the temperature dependence of J_R, H_C, and H_{RC} values are more useful for analysis of NRM carrier grains than is the J_S-T analysis.

In the early stage of the magnetic study of Allende (*i.e.*, SUGIURA *et al.*, 1979) an inconsistency was the Curie point at 320°C and the NRM blocking temperature at 600°C. This disagreement was explained by WASILEWSKI (1982), using the temperature dependence of J_S, H_C and H_{RC} values. He found out the clearly decreased H_{RC} value and small changes in H_C and J_S values at about 320°C, result from the chemical alteration. In the case of Allende, the above condition (2) seems to be a reason for the disagreement between the T_B and Θ_{JS}. The results obtained in this study essentially support his results, although some differences appeared. His data indicated large change of the H_{RC} and small change of the J_S and H_C values at that temperature. In this study, large decay not only with H_{RC} but also with J_R and H_C values at 320°C appeared. However, any small transitions did not appear below 320°C in the J_S-T and X_i-T curves as described by WASILEWSKI (1982). The experimental conditions for the WASILEWSKI (1982) results were different from those in this paper and this could account for discrepancies in the location of minor transitions. The thermal demagnetization curve of Allende showed almost 95% of NRM decay at 320°C. The temperature is completely consistent with the Θ_{JR}, Θ_{HC} and Θ_{HRC}. Therefore, the analysis of temperature dependent of the J_R, H_C and H_{RC} is more significant than that of J_S and X_i for estimation of the phase transition.

Magnetic minerals in ALH-769 are identified as 65% kamacite, and 35% plessite by NAGATA (1979) and FUNAKI *et al.* (1981). The Θ_{JS} at 550°C of plessite is considered to be tetrataenite. The coercivity changed from large $H_C=16.3$ mT and $H_{RC}=122.7$ mT to small $H_C=8.6$ mT and negligible small H_{RC} due to the disorder under heat treatment and the feature in the J_S-T curve is related to the magnetic change of tetrataenite to taenite. These characteristics may satisfy the identification of tetrataenite (NAGATA and FUNAKI, 1986). The NRM of this chondrite decayed to almost 90% at 500°C during thermal demagnetization, as shown in Fig. 1. The J_R and H_C values decreased to 5% at 560°C and was negligibly small at 640°C in the J_R-T and H_C-T curves. The T_B temperature differs from the Θ_{JS} at 745°C due to kamacite and at 560°C due to disorder. From these viewpoints, the almost all stable NRM up to 560°C seems to be carried by tetrataenite.

The phase transition at 550°C of tetrataenite was clearly defined in the J_S-T curve but it was less clear in the X_i-T curve. The X_i value of tetrataenite is extremely small (high coercivity) compared with that of kamacite (low coercivity). Moreover, any magnetization due to taenite (produced from tetrataenite by disorder) did not appear

Table 1. Basic data of the temperature dependent of hysteresis parameters.

Meteorite	Treatment unit	J_S 10^{-2} Am²/kg	J_R 10^{-3} Am²/kg	H_C mT	H_{RC} mT	X_i $\times 10^{-4}$
Allende	Original	8.60	18.44	16.8	97.9	1.098
	Heated	17.07	10.46	5.4	35.2	1.931
ALH-769	Original	9.48	11.43	16.3	122.7	0.703
	Heated	11.37	1.61	0.86	—	1.792
Nuevo Mercurio	Original	13.95	2.05	1.41	6.5	1.497
	Heated	14.19	1.41	0.91	—	1.534

Meteorite	Treatment unit	T_B °C	Θ_{JS} °C	Θ_{JR} °C	Θ_{HC} °C	Θ_{RC} °C	Θ_{X_i} °C
Allende	Original	320*, ≥600	610*	320*, 560*, 150	330*, 560*, 150	320*, 245, >500	610*, 280, 335, 420
	Heated		610*, 290, 400	590*	590*	—	610*, 445
ALH-769	Original	500*	550*, 745*, 500, 690	560*, 640	560*, 640	560*	755*, 570, 670
	Heated		670*, 405*	240, *etc.*	240, *etc.*	—	670*, 525, 380
Nuevo Mercurio	Original	180*, 330*, 530, ≥630	745*, 475, 530, 560, 590	565*, 700	565*, 700	—	745*
	Heated		655*	650*, 385	385, 650	—	655*

* Main transition temperature.

J_S: Saturation magnetization, J_R: saturation remanent magnetization, H_C: coercive force, H_{RC}: remanent coercive force, X_i: initial susceptibility, T_B: Curie point, Θ_{JS}: transition of J_S, Θ_{JR}: transition of J_R, Θ_{HC}: transition of H_C, Θ_{RC}: transition of H_{RC}, Θ_{X_i}: transition of X_i.

at temperatures higher than 550°C on passing its Curie point. Consequently a clearly defined phase transition at 550°C in the X_i-T curve was not observed.

The main magnetic mineral of Nuevo Mercurio is estimated as 6Ni94Fe (kamacite) from the phase transition of Θ_{JS} at 745°C in the heating curve and Θ_{JS} at 655°C in the cooling curve. Since other small Curie points were recognized at 475° and 530°C *etc.* in the heating curve (Table 1), a small amount of taenite and tetrataenite are considered to be present in this chondrite. The large T_B at 180° and 330° of this chondrite may be related to the soft magnetic component which was AF-demagnetized to 67% by 5 mT. The T_B at 530°C seems to result from the more stable NRM noted in the thermal demagnetization curve between 330° and 530°C. The J_S-T and X_i-T curves showed large Θ_{JS} and Θ_{Xi} values at 745°C, but the T_B temperature was independent of these values. The reason of this disagreement may be explained by the above condition (1). A large transition at 565°C in the J_R-T and H_C-T curves is consistent with the T_B at 530°C. Since the J_R and H_C values decreased abruptly just before their transition at 565°C, the

NRM is possibly carried by tetrataenite. In the case of the Nuevo Mercurio, the measurement of the temperature dependence of J_R, H_C and H_{RC} values are useful for the NRM analysis.

5. Conclusion

The characteristics of the temperature dependence of J_R, H_C and H_{RC} values give useful information for the analysis of the T_B resulting from high coercivity grains. As the J_R-T curve showed similarity with the H_C-T curve, measurement of the temperature dependence of SIRM is useful for analysis of the high coercivity grains. However, it is nearly impossible to obtain the information from high coercivity grains using the J_S-T and X_i-T curves, when the amount of high coercivity grains is small. Instead of the measurement for the temperature dependence of coercivity, that of the SIRM measurement may give useful information for the high coercivity grains. The T_B temperature at 320°C in the Allende is apparent due to the coercivity change during heat treatment as was suggested by WASILEWSKI (1988). In the case of ALH-769 and Nuevo Mercurio, tetrataenite is the only significant NRM carrier identified by the J_R-T and H_C-T curves.

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