Acquisition of shock remanent magnetization for demagnetized samples in a weak magnetic field (7 µT) by shock pressures 5–20 GPa without plasma-induced magnetization

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Abstract—Demagnetized samples of cobalt precipitates in a copper matrix were shocked to 5, 10, and 20 GPa in a weak magnetic field of 7.7 µT to elucidate the origins of the natural remanent magnetization of meteorites and the magnetic anomalies of impact craters on the moon and Mars. The samples placed in the target acquired shock remanent magnetization (SRM) whose intensity increased up to 21.3 times compared with the demagnetized state, but SRM intensity and shock intensity were not correlated. The SRM direction was in most cases approximately perpendicular to the shock direction. The samples placed 4.8 mm from the impacted surface did not acquire significant magnetization, suggesting no plasma-induced remanent magnetization (PIRM) up to 20 GPa. When the samples were divided into 8 sub-samples, the SRM intensities of sub-samples increased up to 40 times compared with bulk ones and their directions were scattered. Higher coercive force grains were magnetized perpendicular to the shock direction for shocks of 5 and 10 GPa, but at 20 GPa the directions were less systematically oriented. These results suggest that the proposed plasma-induced magnetization of impactites should be reconsidered.

INTRODUCTION

Every meteorite experiences severe shock due to hypervelocity impact when a parent body is crushed by collision with an other asteroid. Shock effects of ordinary chondrites were inferred from the random directions of natural remanent magnetization (NRM) (e.g., Funaki et al. 1981; Morden and Collinson 1992) and the relation between anisotropy magnetic susceptibility and shock degree (Gattacceca et al. 2005). However, it is not clear whether the NRM of meteorites can survive the shocks. The NRM of impactites, which causes magnetic anomalies (shock magnetization and shock demagnetization) of the impact craters on the moon and Mars, might suffer the magnetic change by shock as well as meteorites. The relation between severe shock and magnetization is important to understand the magnetic acquisition mechanism of impactites and paleomagnetic study of extraterrestrial substances.

The change of remanent magnetization by static stresses (tens of MPa) was described as piezo-remanent magnetization by Nagata (1970), affecting only the lower part of the coercivity spectrum. The effect of the dynamic pressure up to 5 GPa on remanent magnetization has been less studied and is a more complicated problem than that of the static stresses. Pohl et al. (1975) reported shock remanent magnetization (SRM) at shock levels of 0.25–1.0 GPa using terrestrial basalt (projectile speed: 20–160 m/s). The SRM is proportional to the intensity of the applied field and increases with the peak stress applied, and it can be demagnetized by an AF field less than 20 mT. A dependence of the SRM direction on the applied magnetic field has not been found. They interpreted the irreversible movements of a 90° domain wall proposed by Nagata (1971) as the SRM acquisition mechanism. Cisowski and Fuller (1978) reported the SRM characteristics up to 1.0 GPa. Their results were similar in many aspects to those of Pohl et al. (1975), but the difference was found in the SRM direction which relates to the ambient field direction. They inferred the presence of local impact-related magnetic fields as a source magnetization of lunar rocks based on the results of their studies. Smka et al. (1979) showed the acquisition of SRM by an impact of aluminum and basalt at velocity of 13–15 km/s. Kletetschka et al. (2004) showed that pressures of about 1 GPa are sufficient to partially demagnetize all of magnetite, hematite, and titanohematite.
Wasilewski (1976, 1977) and Dickinson and Wasilewski (2000) reported remanent magnetization acquired by shock to 5 GPa in magnetic and nonmagnetic environments using samples containing precipitated grains of anti-ferromagnetic iron (nonmagnetic fcc-phase) in a copper field. The iron grains are transformed to the ferromagnetic bcc-phase by the shock. They named the kind of magnetization as transformation remanent magnetization (TRMR). TRMR is deflected from the ambient magnetic field direction by 30–45° due to preferentially activated (111) slip planes, and the TRMR intensity is 1–2 orders of magnitude less than expected for thermal remanent magnetization (TRM). Crawford and Schultz (1991, 1993) studied the plasma-induced remanent magnetization (PIRM) due to the magnetic field resulting from impact-generated plasma, where the projectiles (spherical aluminum, nylon, iron, and copper) collide with the target (dolomite powder, silica powder and aluminum plate) with a velocity of 4–6.0 km/s. The impact-generated magnetic field is regulated by impact angle as well as velocity and projectile/target composition (e.g., tens of nT at several ten cm from the target when the impact angle is 30°).

From these studies, change in remanent magnetization takes place when dynamic stress is less than 5 GPa. The present study contributes to elucidate which mechanism, SRM or PIRM, more significantly affects remagnetization of shocked samples at dynamic pressures 5, 10, and 20 GPa.

SAMPLES AND A SINGLE-STAGE PROPELLANT GUN

Artificial copper-cobalt samples were used in this study because this material is more durable than rocks against severe shocks and has well-known fundamental magnetic properties (e.g., Becker 1958; Kobayashi 1961; the alloy Cu 98% Co 2% can be quenched as a paramagnetic or superparamagnetic solid solution, with susceptibility of less than 10⁻⁴ Am²/kg, and then the magnetic precipitate is formed by aging. Pellets of electrolytic copper (99.9%) and cobalt (99.9%) were mixed in the ratio of 98 wt% and 2 wt% respectively and were melted in nitrogen gas in a graphite sample holder at about 1600 °C by an induction furnace at the Institute for Materials Research, Tohoku University, Japan. The magnetic properties of cobalt are represented as hexagonal crystallography with a c-axis of the easy magnetization, Curie point (Tc) = 1131 °C and saturation magnetization (Is) = 161 Am²/kg (at 15 °C). The melting point of Co is 1495 °C and there is no phase transition known under the high pressure. Ingots of 100 mm length and 15 mm diameter were encapsulated in quartz tubes in vacuum (10⁻¹ Pa), and were heated at 1000 °C for 50 hr. After heat treatment, they were quenched in water in the laboratory magnetic field (45900 nT). The magnetization of these ingots was weak, at intensity R = 1.15 × 10⁻⁴ Am²/kg. The ingots were heated again to 750 °C for 50 min in the same vacuum condition for precipitation of Co crystals, and were immediately quenched in water. The magnetization was increased to R = 8.29 × 10⁻³ Am²/kg by this aging. Probably solid solution of CuCo was partially produced in the first aging and ferromagnetic Co grains were precipitated in the second aging. Samples #1 to #3, #A and #B and #P1 to #P3 of 10 mm diameter and length were cut out from the ingots using a lathe. The directions of samples were marked on the tops with an arbitrary direction and were stored in a μ-metal shield case throughout the experiment to avoid magnetic contamination.

In order to discriminate the SRM from the PIRM, inner samples (sample #1, #2, #3) were placed in a target (sample holder) behind the collided surface of a flyer, and outer samples (#P1, #P2, #P3) were placed by a side of that surface, as shown in Fig. 1. The inner samples were surrounded by two kinds of Cu-holders and a nonmagnetic stainless-steel holder (SUS304-holder). The outer samples wrapped with 1 mm thick rubber were bonded to the SUS304-holder. The distance between the collided surface and the top of the inner sample was 10 mm; the space between the flyer and the outer sample was 4.8 mm when the flyer just touched the Cu-holder. The sample holders were set in a single-stage propellant gun installed at Tohoku University (Goto and Syono 1984), adjusting the z axis of the inner sample and the projectile as shown in Fig. 1, where the right-hand coordinate system (+x to upward) is employed. The magnetic field (h) in the inner sample was reduced to about h = 7.7 μT (parallel to the +z axis) by a single-layered μ-metal pipe.

A Teflon flyer 25 mm in diameter and 5 mm thick bonded on a projectile 25 mm in diameter and 30 mm long consisting of a polyethylene and polycarbonate, was used at dynamic pressure 5 GPa. When pressures of 10 and 20 GPa were produced, an aluminum plate 5 mm thick and a SUS-304 plate 3 mm thick were used, respectively, instead of the Teflon flyer, as shown in Fig. 1. Gunpowder 15 g for 5 and 10 GPa and the powder 20 g for 20 GPa were used, respectively. The velocity of the projectile was controlled to 800 m/s with precision of less than 1% using an empirically established relation between the amount of gunpowder and the mass of the flyer. The shock pressures 5, 10, and 20 GPa were calculated from the velocity and the density of flyers on the basis of the impedance match.

The inner sample encapsulated in the sample holder was recovered within 5 min after the shock loading. The temperature increase during shock compression is estimated to however no higher than 100 °C even under shock loading to 20 GPa. Actually the collision surface was slightly hot (about 40 °C after a few minutes from shock loading) just after recovery of the holder of the 20 GPa experiment, so acquisition of TRM by the samples is ruled out. The Cu-holders were swollen and distorted around the collision surface and their influence can be seen to reach the supporter through
the SUS-304 holder, even at the shock of 5 GPa. This phenomenon was more conspicuous at 20 GPa. Even though there is deformation of the holders, the sample and Cu-holders were not displaced from the SUS-304 holder. The sample holders were knocked off to the recovery chamber along with the outer sample and supporter by the shock. After shock loading, the Cu-holder was removed from the supporter and the SUS-304 holder by a metallic cutter using cooling water, then the outer Cu-holder was removed from the inner Cu-holder using a lathe. As the inner sample could not be separated from the inner Cu-holder without damage, due to adhesion resulting from the shock, the inner sample with the inner Cu-holder was utilized for magnetic studies of the bulk sample.

**BASIC MAGNETIC PROPERTIES OF THE NON-SHOCKED SAMPLE**

The sample #A having NRM of intensity \( R = 2.61 \times 10^{-3} \text{ Am}^2/\text{kg} \), inclination \( I = 67^\circ \), declination \( D = 351^\circ \), was divided into 8 sub-samples (\#A-1 to \#A-8, 0.25–0.58 g) with the orientation shown in Fig. 2. The NRM intensities of sub-samples were \( R = 2.26 \pm 0.23 \times 10^{-3} \text{ Am}^2/\text{kg} \) and the mean direction was \( I = 70^\circ, D = 17^\circ \) with cone of confidence of 95% probability, \( \alpha_{95} = 6.2^\circ \), as shown in Fig. 2. As the NRM directions of the sub-samples are the same as that of bulk sample #A, considering the \( \alpha_{95} \) value, NRM seems to be uniform in the sample.

The sample #B was demagnetized to 100 mT in steps of 5 mT. The NRM intensity \( (1.01 \times 10^{-2} \text{ Am}^2/\text{kg}, I = −73^\circ, D = 58^\circ) \) showed a decrease rapidly to 30 mT, then more gradual to \( 7.09 \times 10^{-4} \text{ Am}^2/\text{kg} \) at 100 mT, as shown in Fig. 3. The NRM direction of the sample was stable throughout the demagnetization. After the AF demagnetization, the sample #B was divided into 8 sub-samples (\#B-1 to \#B-8) by a metallic cutter using cooling water in the geomagnetic field (45900 nT), the average NRM of these sub-samples \( (I = −63^\circ, D = 108^\circ, \alpha_{95} = 8.4^\circ, \text{precision parameter (K) = 45}) \) showed an increase of intensity up to \( 1.559 \pm 0.223 \times 10^{-3} \text{ Am}^2/\text{kg} \) where the additional remanence was about \( 8.505 \times 10^{-4} \text{ Am}^2/\text{kg} \), about 8% of the original NRM intensity. The change in normalized intensity and the direction before and after demagnetization to 100 mT for the sub-samples are shown in Fig. 3. The average intensity showed a rapid decrease on demagnetization to \( 9.443–1.369 \times 10^{-4} \text{ Am}^2/\text{kg} \) to 10 mT, then became flat to 100 mT, though the sub-sample #B-1 showed some zigzag variations, estimating the larger Co grains were included. The intensity at 10 mT was \( 8.271–1.060 \times 10^{-4} \text{ Am}^2/\text{kg} \), comparable to that of the bulk sample after AF demagnetization. The directions of the sub-samples were stable throughout the demagnetization and were clustered at \( I = −60^\circ, D = 119^\circ, K = 37, \text{ and } \alpha_{95} = 9.2^\circ \) for the state of NRM and AF demagnetization to 100 mT. Therefore, the magnetic contamination was acquired in the samples during cutting, but it is weak and removable by AF demagnetization to 10 mT. When the saturation remanent magnetization (SIRM) was acquired to the sub-samples \#B-2, −6, and −8 at 1.0 T of the external magnetic field, the intensity was \( 2.56–0.39 \times 10^{-1} \text{ Am}^2/\text{kg} \), which is 25.35 times larger than the NRM intensity of sample #B.
INNER SHOCKED SAMPLES

Magnetic Properties of the Bulk Samples

Before shock loading, inner samples were demagnetized by the AF field to 100 mT. The variation of the remanent magnetization of AF demagnetization and shock loading is summarized in Table 1 and Fig. 4. The intensities of the remanent magnetization were decreased by almost one order without a large change of direction, except for sample #1, which might be interpreted as magnetic contamination during sample preparation using the lathe. The magnetization of sample #1 increased to $3.86 \times 10^{-3}$ Am$^2$/kg after shock loading to 5 GPa, which is 7.43 times the increase, and was comparable to the NRM intensity. The NRM direction of sample #1 after AF demagnetization to 100 mT changed considerably, from $I = -1^\circ$, $D = 100^\circ$ to $I = 21^\circ$, $D = 167^\circ$; then it was changed drastically to $I = 14^\circ$, $D = 62^\circ$ by shock loading to 5 GPa.

The remanence of sample #2 increased to $3.47 \times 10^{-3}$ Am$^2$/kg, an increase of 2.16 times, by shock loading to 10 GPa, while it was only 0.250 times the original NRM. The NRM direction, $I = -8^\circ$, $D = 190^\circ$, showed small change by AF demagnetization to 100 mT, but it was shifted to $I = 21^\circ$, and $D = 215^\circ$ after the shock loading.

The sample #3 gained extremely large remanence, $1.380 \times 10^{-2}$ Am$^2$/kg, by 20 GPa shock loading, showing an increase of 21.33 and 5.17 times larger than the intensity of demagnetization to 100 mT and NRM, respectively. The direction of this sample $I = -8^\circ$, $D = 322^\circ$ showed minor change by AF demagnetization to 100 mT, while there was a drastic shift in direction, $I = -11^\circ$, $D = 74^\circ$, after 20 GPa shock loading.

The intensity of the magnetization, after shock loading to 5, 10, and 20 GPa, increased in each case and particularly strongly at 20 GPa (7.43, 2.16, and 21.33 times, respectively), but not proportional to the shock pressures intensity. Although the direction after AF demagnetization was dispersed by shock loading, the inclination remained in the range of low inclination between $-11^\circ$ and $21^\circ$. From these observations, it can be concluded that the inner samples acquired the remanent magnetization in a direction nearly perpendicular to the shock direction. This is similar remanence to SRM as proposed by Pohl et al. (1975).

Magnetization of the Sub-Samples

The samples after shock loading were cut into 8 fan-shaped sections (about 4 mm wide and 4 mm long) without disturbing their orientations using a thin-wheel cutter with cooling water, as shown in Fig. 5. These sub-samples were named #1-1 to #1-8 for sample #1 (5 GPa), #2-1 to #2-8 for sample #2 (10 GPa) and #3-1 to #3-8 for sample #3 (20 GPa). The SRM directions and intensities of these sub-samples are shown in Fig. 5. The mean direction of these samples was $I = -5^\circ$, $D = 7^\circ$ with $\alpha_{95} = 71^\circ$ and $K = 2$. The directions of sub-samples #1-1, #1-2, #1-4, #1-6, #1-7, and #1-8 make a loose cluster around that of the bulk sample #1 with intermediate ($I = \pm 30^\circ$ to $\pm 50^\circ$) to low inclination ($I = 0^\circ$ to $\pm 30^\circ$), while
those of the sub-samples #1-3 and #1-5 magnetized to low inclination showed dispersion widely from the cluster. The directions of the sub-samples #2-1 to #2-8 were distributed widely ($\alpha_{95}$=90 and K=0) in middle to low inclinations without any relation to the direction of the bulk sample #2. Those of sub-samples #3-1 to #3-8 also showed wide scatter among high to low inclinations (whole range in inclination, the mean direction $I = -4^\circ$, $D = 280^\circ$ with $\alpha_{95}$ = $45^\circ$ and K = 1) without relation to the bulk magnetization.

The SRM intensities of sub-samples #1-1 to #1-8 after shock loading 5 GPa showed a wide range of variation from $1.73 \times 10^{-2}$ to $1.31 \times 10^{-1}$ Am$^2$/kg, 4.5 to 40 times stronger than that of bulk sample #1. Sub-samples #2-1 to #2-8, shock loaded to 10 GPa, were magnetized to $1.77 \times 10^{-2}$ to $7.27 \times 10^{-2}$ Am$^2$/kg, 5.1–21 times stronger than the bulk sample #2. The intensities of sub-samples #3-1 to #3-8, shock loaded to 20 GPa, were $1.52 \times 10^{-2}$ to $5.69 \times 10^{-2}$ Am$^2$/kg, an increase of 1.1 to 4.1 times compared with bulk sample #3. In general, the SRM intensity seems to be larger for the samples of shock loading to 5 GPa than 10 and 20 GPa.

**AF Demagnetization of the Sub-Samples**

The sub-samples were demagnetized by AF field up to 100 mT in steps of 5 mT. The variations of direction and normalized intensity are plotted in Fig. 6, in addition to the SRM directions of the bulk samples. For shock loading of 5 GPa, the sub-samples #1-2 and #1-4 showed large excursions of direction with a shift from $I = -49^\circ$, $D = 85^\circ$ to $I = -27^\circ$, $D = 235^\circ$ and from $I = 13^\circ$, $D = 143^\circ$ to $I = 7^\circ$, $D = 334^\circ$, respectively. Relatively small shifts in direction toward low inclination appeared on sub-samples #1-3 and #1-5, where the inclinations were changed from $I = 54^\circ$ to $25^\circ$ and $I = -49^\circ$ to $-27^\circ$, respectively. Sub-samples #1-1 and #1-7 also showed small shifts toward the horizon, whereas #1-8 and #1-6 did not show any significant change of direction in the low inclination area. Since the directions after AF demagnetization to 100 mT
were directed toward lower inclination within $I = \pm 27^\circ$, high coercivity grains seem to be directed to the horizontal, while low coercivity grains seem to be magnetized to variable directions. The SRM intensities of these sub-samples, except #1-4, show relatively steep demagnetization up to 30 mT and a gradual decrease on demagnetization to 100 mT. The intensity of sub-sample #1-4 showed a steep decrease up to 25 mT, and then became gradual with a hump. This phenomenon is explained by superposition of the opposite directions of soft and hard remanence, as plotted in the direction change of sub-sample #1-4 in Fig. 6.

Sub-samples from #2-1 and #2-8, subjected to a shock of 10 GPa, showed gradual change of demagnetization curves for the direction. Inclinations ranging between $I = -43^\circ$ and $51^\circ$ shifted to $I = -3^\circ$ to $25^\circ$ upon demagnetization to 100 mT. The intensity of sub-sample #1-4 showed a steep decrease up to 25 mT, and then became gradual with a hump. This phenomenon is explained by superposition of the opposite directions of soft and hard remanence, as plotted in the direction change of sub-sample #1-4 in Fig. 6.

For the sub-samples which were shocked to 20 GPa, the directions of #3-5 and #3-7 showed small shifts to lower inclination, and those of #3-2 and #3-8 were demagnetized from intermediate to low inclinations by AF demagnetization. The sub-sample #3-6 showed unstable curves resulting in large excursion with a change in inclination from $I = 37^\circ$ to $I = 55^\circ$. The directions of the other sub-samples #3-1, #3-3, and #3-4 indicated small shifts in the higher inclination area, being not demagnetized toward low inclination. The AF demagnetization curves of the intensity were more variable than those of samples which were shocked to 5 and 10 GPa. The intensities in cases of sub-samples #3-4 and #3-5 decreased gradually to 35 mT and then it was gradual. The other sub-samples showed intermediate curves with small perturbations in the low demagnetization field.

### OUTER SAMPLES

**Magnetic Properties of the Bulk Samples**

Fairly uniform NRM intensities were observed in the outer samples #P1, #P2, and #P3. They decreased less than 17% of the NRM by AF demagnetization to 100 mT, as shown in Table 1. The NRM directions were stable throughout the demagnetization. The demagnetized outer samples were placed beside the impacted surface, shock loaded to 5, 10, and 20 GPa, and the variation of remanence is shown in Table 1 and Fig. 7. These samples were partially deformed on the surface on the collision side, and also on the opposite side, after shock events due to collisions with projectile fragments and the SUS-304 pipe, as shown in the figure. After shock to 5 GPa, the intensity of remanence of sample #P1 showed almost no change. At shocks of 10 and 20 GPa, these of samples #P2 and #P3 showed increases to

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**Table 1. Variations of magnetization of the NRM; NRM after AF demagnetization to 100 mT and SRM.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shock (S)</th>
<th>R (Am$^2$/kg) ratio</th>
<th>I</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>#A</td>
<td>–</td>
<td>NRM 2.61E-03</td>
<td>–</td>
<td>67</td>
</tr>
<tr>
<td>#B</td>
<td>–</td>
<td>NRM 1.01E-02</td>
<td>–</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 9.03E-04</td>
<td>0.09</td>
<td>–62</td>
</tr>
<tr>
<td>#1 (8.43 g)</td>
<td>5 GPa</td>
<td>NRM 3.82E-03</td>
<td>–</td>
<td>–1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 5.20E-04</td>
<td>0.14</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SRM 3.86E-03</td>
<td>7.42</td>
<td>14</td>
</tr>
<tr>
<td>#2 (8.38 g)</td>
<td>10 GPa</td>
<td>NRM 1.39E-02</td>
<td>–</td>
<td>–8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 1.61E-03</td>
<td>0.12</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SRM 3.47E-03</td>
<td>2.16</td>
<td>21</td>
</tr>
<tr>
<td>#3 (8.50 g)</td>
<td>20 GPa</td>
<td>NRM 2.67E-03</td>
<td>–</td>
<td>–8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 6.47E-04</td>
<td>0.24</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SRM 1.38E-02</td>
<td>21.33</td>
<td>–11</td>
</tr>
<tr>
<td>#P1 (6.98 g)</td>
<td>5 GPa</td>
<td>NRM 1.08E-02</td>
<td>–</td>
<td>–72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 9.35E-04</td>
<td>0.09</td>
<td>–52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma 9.60E-04</td>
<td>1.03</td>
<td>–58</td>
</tr>
<tr>
<td>#P2 (6.93 g)</td>
<td>10 GPa</td>
<td>NRM 1.08E-02</td>
<td>–</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 1.74E-03</td>
<td>0.16</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma 2.92E-03</td>
<td>1.68</td>
<td>67</td>
</tr>
<tr>
<td>#P3 (6.91 g)</td>
<td>20 GPa</td>
<td>NRM 1.09E-02</td>
<td>–</td>
<td>–77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AF demag 9.47E-04</td>
<td>0.09</td>
<td>–58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasma 3.39E-03</td>
<td>3.58</td>
<td>–13</td>
</tr>
</tbody>
</table>

R: intensity of remanent magnetization; I: inclination; D: declination; NRM: natural remanent magnetization; AF demag: after AF demagnetization to 100 mT; SRM: shock remanent magnetization.
Fig. 4. Intensity and direction variations of NRM, after AF demagnetization to 100 mT (AFdemag) and after shock loading of 5, 10, and 20 GPa for inner samples #1 (circle), #2 (square), and #3 (triangle). In the direction plots, solid symbols denote downward inclination and open ones denote upward inclination.

Fig. 5. The magnetization variations of the inner samples after shock loading and their sub-samples. Solid (open) circles denote downward (upward) inclination of a sub-sample and solid (open) squares denote downward (upward) inclination of a bulk sample. Straight lines on the intensity spectrum denote the SRM intensity of bulk samples. The number of sub-samples and cutting lines are described on the cylindrical sample figure.
1.68 and 3.58 times, respectively. There was a small change in
direction of remanence for samples #P1 (5 GPa) and #P2
(10 GPa), but that of sample #P3 (20 GPa) showed a major
shift of inclination from $I = -53^\circ$ to $-13^\circ$.

**Magnetization of the Sub-Samples**

The outer samples after the shock event were cut into 8
sub-samples as for the inner samples. These sub-samples
were named sub-samples #P1-1 to #P1-8 for sample #P1,
#P2-1 to #P2-8 for sample #P2, and #P3-1 to #P3-8 for sample
#P3. Sub-samples #P1-1 to #P1-4, #P2-1 to #P2-4, and #P3-1
to #P3-4 included a possibility of deformed portions. The
intensities and directions of these sub-samples are shown in
Fig. 8 along with those of their bulk samples after AF
demagnetization to 100 mT. Sub-samples #P1-1 to #P1-4,
excluding #P1-2, of shock 5 GPa showed almost the same
intensity as that of the bulk one ($9.35 \times 10^{-4}$ Am$^2$/kg), but
the deformed sub-sample #P1-2 increased in intensity. The
directions of these sub-samples (the mean direction $I = -52^\circ$,
$D = 322^\circ$ with $\alpha_{95} = 47^\circ$ and $K = 2$) show scatter around that
of the bulk sample ($I = -52^\circ$, $D = 287^\circ$) after AF
demagnetization to 100 mT, but those of #P1-2 and #P1-4
were apart from that of sample #P1.

In case of 10 GPa, the deformed portions were
observed on the sub-samples #P2-1, #P2-2 and #P2-4.
Sub-sample #P2-2 showed increases in intensity, while
the other 7 sub-samples did not show any increase in
magnetization compared to that of the bulk sample #P2
($1.74 \times 10^{-3}$ Am$^2$/kg). The directions of these samples
formed a loose cluster (the mean direction $I = 47^\circ$, $D = 148^\circ$
with $\alpha_{95} = 24^\circ$ and $K = 6$) around that of sample #P2 ($I = 66^\circ$, $D = 133^\circ$).

In the cases of the sub-samples #P3-1 to #P3-8 subjected
to shock to 20 GPa, the 2 sub-samples #P3-1 and #P3-3
included the deformed portion on the surfaces. The intensities
of remanent magnetization of these deformed sub-samples
increased drastically as shown in Fig. 8, but the other 6 sub-
samples decreased the intensity from that of sample #P3. The
directions showed scatter (the mean direction $I = -44^\circ$, $D = 321^\circ$
with $\alpha_{95} = 31^\circ$ and $K = 4$) from those of the bulk sample
after AF demagnetization to 100 mT ($I = -58^\circ$, $D = 305^\circ$) and
shock exposure ($I = -13^\circ$, $D = 279^\circ$).

The intensity increase in the outer samples is loosely
related to the sample deformation, although the direction was
disturbed by the shock event as distribution around the bulk
samples before AF demagnetization.

**AF Demagnetization of the Sub-Samples**

All the sub-samples were demagnetized to 100 mT in
steps of 5 mT. The normalized intensity and direction

![Image of AF demagnetization curves for sub-samples of inner samples.](image-url)
Fig. 7. The magnetization variations before and after 5, 10, and 20 GPa shock events for the outer samples #P1, #P2, and #P3. In the direction, a solid symbol denotes downward inclination and an open symbol denotes upward inclination. The deformed portion of the outer sample was described on the cylindrical sample figure. The numbers of sub-sample and cutting lines are described on the sample figure.

Fig. 8. The magnetization variations of the outer samples and their sub-samples after shock events. Solid (open) circles denote downward (upward) inclination of sub-samples and solid (open) squares denote downward (upward) inclination of bulk samples. Straight lines on the intensity spectrum denote the intensity of remanent magnetization after a shock event for bulk samples.
changes are shown in Fig. 9. In case of shock to 5 GPa, the intensities of sub-samples #P1-1, #P1-2, and #P1-3 decreased smoothly up to 100 mT whereas sub-sample #P1-4 showed a steep gradient in the curve forming the lowest intensity around 40 mT. The directions of these sub-samples showed larger excursions, especially that of sub-sample #P1-4. In contrast, sub-samples #P1-5 to #P1-8 showed very flat intensity decay curves between 10 and 100 mT under AF demagnetization. The directions of sub-samples having stable intensity indicated small variations throughout the demagnetization.

The sub-samples #P2-1 and #P2-2 which were shocked to 10 GPa showed gradual decrease in intensity in the demagnetization curves, while those of the sub-samples #P2-6 and #P2-8 showed steep gradients under demagnetization between 0 and 30 mT, but they were almost flat between 30 to 100 mT. A large convex curve was observed in sub-sample #P2-4. The sub-samples #P2-3, #P2-5, and #P2-7 did not show large intensity change throughout the demagnetization, except between 0 and 10 mT. The direction changes of every sub-sample were small on demagnetization, although the inclination of the sub-sample #P2-4 was inverted from upward to downward.

The sub-samples shocked to 20 GPa exhibited large intensity decay curves, especially sub-samples #P3-1 and #P3-3, and a relatively large decay curve in case of sub-sample #P3-4. The other sub-samples showed almost flat demagnetization curves between 20 and 100 mT. The directions of these sub-samples were relatively stable against demagnetization as were the sub-samples subjected to shock exposure of 10 GPa.

**DISCUSSION**

The spectrum of NRM intensities having an average of $2.26 \pm 0.23 \times 10^{-3}$ Am$^2$/kg with the directions of $\alpha_{95} = 6.2^\circ$ for sub-samples #A1 to #A8 (Fig. 2) satisfied the condition that the CuCo sample is magnetically uniform enough for shock experiments. The gradually decreasing AF demagnetization curve of the bulk sample #B (Fig. 3) indicated variable coercivity of magnetic grains from the multi-domain (MD) to the single-domain (SD). Magnetic contamination such as isothermal remanent magnetization (IRM) and viscous remanent magnetization (VRM) may be negligible, if the small $\alpha_{95}$ value is taken into consideration. Although the bulk samples were cut into 8 sub-samples in this study, the magnetic disturbance due to the cutting effect is only 8% of the NRM intensity, that is demagnetized before 10 mT.

The SRM direction acquired by inner samples was not deflected to the direction of the external magnetic field (7.7 $\mu$T, parallel to the $+z$ axis), but it was directed to almost perpendicular to the shock propagation direction. Although the SRM intensity of sample #3 shocked to 20 GPa was much larger than that of samples #1 (5 GPa) and #2 (10 GPa), the intensities of sub-samples of sample #3 were generally weaker than those of others. Thus, the SRM intensity of bulk samples seems to be unrelated to the shock level between 5 and 20 GPa. Pohl et al. (1975) did not recognize any
dependence of SRM on the direction of an applied magnetic field of less than 1 mT, while Cisowski and Fuller (1978) reported that the direction of SRM is related to the ambient field (about 10 μT) direction at the time of impact. Our results support the former study, although the applied magnetic field was as weak as 7.7 μT.

The distribution of SRM of the inner samples is much more complicated than that of terrestrial basalt, as scattered direction in one sample. A plausible explanation for such magnetic structure is as follows. The direction of remanent magnetization of bulk samples after AF demagnetization to 100 mT was reasonably uniform as the confidence of $\alpha_{95} = 9.2^\circ$ (Fig. 3). After shock loading, the sub-samples from the inner samples were strongly magnetized, more than the bulk one, and the directions were scattered widely. The SRM direction after AF demagnetization to 100 mT was shifted to perpendicular ($I < \pm 30^\circ$) to the shock direction for 5 and 10 GPa and nearly parallel ($I = \pm 55^\circ$ to $\pm 90^\circ$) or perpendicular one for shock loading to 20 GPa. No traces of the original direction of the bulk sample before shock loading could be confirmed in the sub-samples, even if they were demagnetized. Therefore, it can be concluded that the remanent magnetization which survived AF demagnetization to 100 mT was completely replaced by SRM.

The directional variation of the inner sub-samples against AF demagnetization was characterized by a smooth shift from the middle to low inclination for 5 and 10 GPa, suggesting that low coercive force (Hc) grains were magnetized to intermediate inclination but higher Hc grains were magnetized to low inclination (perpendicular to the shock propagation). In the case of 20 GPa, high to low inclination appeared in sub-samples. The high inclination of remanence did not shift to lower inclination during demagnetization. If the SRM direction is controlled by only the magnetic anisotropy that is yielded by strain and deformation of the magnetic grains by shock, the observed higher inclination in the sub-samples shocked to 20 GPa cannot be explained because the magnetically easiest plane is perpendicular to the shock. Therefore, the other mechanisms should be strongly affected by the origin of SRM in addition to the anisotropy.

These characteristics of SRM may be explained due to the presence of small magnetic domains, where the domains are magnetized in the plane perpendicular to the shock direction for shocks 5 and 10 GPa, and in the almost parallel direction in addition to the perpendicular plane for shock 20 GPa. A plausible explanation of the former directions is due to magnetic anisotropy, while some interference of the reflected shock waves may act on the realignment of the magnetization of domains by stronger shock of 20 GPa in the latter case. When the sub-samples are too small, as our sub-sample (about 4 mm wide and 4 mm long in fan-shaped sections), the observed direction does not represent the SRM of the bulk sample and the intensity is usually stronger than that of the bulk sample. The NRM of ordinary chondrites should be reconsidered from the viewpoint of SRM, because the scattered NRM directions, stronger intensity and AF demagnetization curves of ordinary chondrites (e.g., Funaki et al. 1981; Morden and Collinson 1992) seem to be resemble SRM obtained from this study.

Although the remanence of the outer samples #P1, #P2, and #P3 increased of the intensity to 1.03, 1.68, and 3.58 times after shock loading of 5, 10, and 20 GPa respectively, the acquired magnetization was limited to the deformed portions of samples by collision with projectile fragments and an SUS304-pipe. The intensity of the non-deformed portions was similar to the magnetization of the bulk sample before the shock loading. The AF demagnetization curves (Fig. 9) of the non-deformed portions resemble to those of the non-shocked sub-samples #B-1 to #B-8 (Fig. 3). The intensities of the inner samples #1, #2 and #3 increased to 7.43, 2.16, and 21.33 times after shock loading of 5, 10, and 20 GPa respectively. The remanence of the inner sub-samples remarkably increased from 1.1 to 40 times compared with their bulk samples and their AF demagnetization curves differed to those of the non-shocked sub-samples #B-1 to #B-8. Therefore, the inner samples seem to be acquired of the significant magnetization by the shock loading. If PIRM is responsible for the remagnetization as proposed by Crawford and Schultz (1991), the stronger magnetization is gained in the outer samples than in the inner samples, because the shortest distance between the flyer and the outer sample is 4.8 mm, and is 10 mm between the flyer and the inner sample at the shock event. From this evidence, we conclude that the PIRM might not be yielded in this study. It may be reasonable due to much slower projectile velocity (only 0.8 km/s) in this study compared with much faster velocity (5.2 to 6.0 km/s) as Crawford and Schultz (1991) claimed the PIRM.

Carporzen et al. (2005) found strongly magnetized and randomly oriented directions changing over centimeter length scales at the Vredefort meteorite crater in South Africa. They attributed the unusual magnetization to PIRM. If the plasma-induced magnetic field pulsating over several milliseconds (Crawford and Schultz 1991) is the main reason for the random magnetization, the acquired magnetization should be weak, because the pulsating field may act on samples as AF demagnetization. If a steady magnetic field were present during the plasma-induced magnetic field, the sample should be magnetized to the direction of the steady magnetic field as acquisition of an anhysteretic remanent magnetization (ARM). Such complicated magnetization is explained more easily by SRM rather than PIRM. Since SRM is acquired at much lower pressure, 5 to 20 GPa, than PIRM, SRM is a more common magnetization mechanism for impactites.

**CONCLUSIONS**

Weak magnetic copper-cobalt ingots of Cu 98% Co 2% were prepared by quenching after heat treatment at 1000 °C for 50 hr. The magnetic samples resulting from
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