I. Bishunpur: Chondrule Dusty Olivine

- Early Solar System magnetic fields have been resolved from dusty olivine found in unequilibrated chondrites\(^1\).
  - Dusty olivine: forsteritic olivine bearing sub-micron Fe-Ni precipitates (Fig. 1, 2, 3).
  - Present in 1/10 chondrules.
  - Synthetic dusty olivine proves to be a credible paleomagnetic recorder\(^2\).
  - Here we analyse nanoscale magnetic properties of chondrule dusty olivine in Bishunpur with electron holography.

Figure 1 Dusty olivine bearing chondrules in Bishunpur (LLS.1)

III. Off-axis Electron Holography

- TEM samples were prepared using a Helios Nanolab 600 FIB.
  - A Fischione 1040 Nanomill was operated at 500 eV to thin the lamella further.
  - The FEI Titan HOLO TEM was operated at 300 kV in Lorentz mode with a biprism typically at 80 V (Fig. 4).
  - Holograms processed using Semper\(^3\) to remove electrostatic potential contributions to phase images and produce magnetic induction maps (Fig. 6b, 7).

Figure 3 Bright field TEM images of the dusty olivine lamellae prepared in the FIB

- Lorentz lens allows imaging in magnetic field-free conditions (Fig. 5).
- Objective lens only used to saturate sample’s magnetisation (Fig. 6b).
- Interference fringe patterns are generated due to overlap of the vacuum and specimen waves (Fig. 5).
- Fe-Ni grains must be close enough to edge of lamella to facilitate overlap of specimen and vacuum waves.
- The interference fringes provide phase shift information: the sample’s electrostatic potential and magnetic induction.
- Phase information is usually lost in standard TEM imaging.
- Vacuum reference holograms also recorded to remove artifacts in the phase reconstruction due to the instrument (Fig. 6d).

Figure 4 (left) FEI Titan HOLO TEM at the Ernst Ruska Centre, Jülich, Germany fitted with a spherical aberration (C\(_J\)) image corrector, two biprisms, a Lorentz lens, and an 11 mm pole piece gap for ±70° stage tilt.

Figure 5 (right) Diagram illustrates how the biprism causes overlap of vacuum and specimen waves to produce interference fringes.

II. TEM EDX Analysis

- Figure 2 EDX chemical analysis with FEI Titan ChemSTEM at Ernst Ruska-Centre, Jülich, Germany. Corresponding high angle annular dark field images above. TEM operated at 200 kV, with a element mapping resolution of 0.5 nm. Elements displayed are O, Mg, Si, Fe, Al, Ni, Ca. Lamella was prepared with a Focused Ion Beam.

IV. Off-axis Electron Holography: Results

- Inverse Fourier transform of the sideband (Fig. 6e) and unwrapping algorithms are used to obtain phase images (Fig. 6f, g).
- Tilting the sample ±70° allows the opposite magnetic phase contributions to be determined (Fig. 6f, g), which when subtracted, removes the electrostatic potential and leaves the magnetic phase contribution (Fig. 6h).
- Magnetic induction map produced by taking the cosine of phase image (Fig. 7).

Figure 6a Bright field image of Fe-Ni.
Figure 6b Schematic of sample tilt.
Figure 6c Hologram of Fe-Ni.
Figure 6d Reference hologram.
Figure 6e Fourier transform of image (left).
Figure 6f Phase image after saturation at ±70° tilt.
Figure 6g Phase image after saturation at ±70° tilt.
Figure 6h Magnetic phase of sample.

Figure 7 Magnetic induction maps of kamacite grains for which holograms and magnetisation reversal were possible. Color wheel inset indicates the direction of magnetic induction. Contours indicate magnetic flux density.

V. Summary and Conclusions

- Initial EDX analysis of the dusty olivine determined a forsteritic olivine composition with grains of Fe with < 2% Ni.
- Minor Fe oxidation. Lamella stored in ethanol to minimise air exposure.
- Two FIB lamellae had one Fe-Ni grain each close enough to the edge to generate interference patterns (Fig. 2, 3).
- Magnetic induction maps show pseudo-single domain (PSD) behaviour in vortex state, and multi-vortex structure in a larger 700 nm particle (Fig. 7).
- The contour density indicates the particles are strongly magnetic.
- Previous electron holography study of magnetite indicates that PSD grains are credible carriers of magnetisation\(^4\).
- We intend to heat the Fe-Ni grains and observe their remanence at high temperatures.

References


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