EUHEDRAL METALLIC-Fe-Ni GRAINS IN EXTRATERRESTRIAL SAMPLES.

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Metallic Fe-Ni is rare in terrestrial rocks, being largely restricted to serpentinized peridotites and volcanic rocks that assimilated carbonaceous material. In contrast, metallic Fe-Ni is nearly ubiquitous among extraterrestrial samples (i.e., meteorites, lunar rocks and interplanetary dust particles). Anhedral grains are common. For example, in eucrites and lunar basalts, most of the metallic Fe-Ni occurs interstitially between silicate grains and thus tends to have irregular morphologies. In many porphyritic chondrules, metallic Fe-Ni and troilite form rounded blebs in the mesostasis because their precursors were immiscible droplets. In metamorphosed ordinary chondrites metallic Fe-Ni and troilite form coarse anhedral grains. Some of the metallic Fe-Ni and troilite in meteorites and lunar rocks has also been mobilized and injected into fractures in adjacent silicate grains where local shock-reheating temperatures reached the Fe-FeS eutectic (988°C). In interplanetary dust particles metallic Fe-Ni most commonly occurs along with sulfide as spheroids and fragments.

Euhedral metallic Fe-Ni grains are extremely rare. Several conditions must be met before such grains can form: (1) grain growth must occur at free surfaces, restricting euhedral metallic Fe-Ni grains to systems that are igneous or undergoing vapor-deposition; (2) the metal±sulfide assemblage must have an appropriate bulk composition so that taenite is the liquidus phase in igneous systems or the stable condensate phase in vapor-deposition systems; and (3) metallic Fe-Ni grains must remain undeformed during subsequent compaction, thermal metamorphism and shock. Because of these restrictions, the occurrence of euhedral metallic Fe-Ni grains in an object can potentially provide important petrogenetic information. Despite its rarity, euhedral metallic Fe-Ni occurs in a wide variety of extraterrestrial materials. Some of these materials formed in the solar nebula; others formed on parent body surfaces by meteoroid impacts.

Chondrules. Euhedral metallic Fe-Ni grains have been reported in rare chondrules where they crystallized during chondrule formation. Such chondrules probably cooled slowly enough near the crystallization temperature of metallic Fe-Ni to allow formation of euhedral grains instead of spheroidal blebs.

Olivine phenocrysts. Housley [1] reported curvilinear trails of tiny (2 μm) crystals of awaruite (Ni_3Fe) within an olivine grain from a porphyritic olivine chondrule in the Allende CV3 chondrite. The euhedral metallic Fe-Ni grains may have crystallized from the chondrule melt directly onto the surface of the growing olivine; euhedral morphologies developed because of the large difference in surface energy between the crystallizing metallic Fe-Ni and the surrounding silicate-rich liquid.

Opaque nodules. Within an Allende porphyritic olivine chondrule, Rubin [2] found a large (290x510 μm) opaque nodule comprised (in vol.%) of 9% euhedral awaruite grains (typically 35-65 μm), 85% magnetite, 5% pentlandite and 1% merrillite. Haggerty and McMahon [3] had suggested that such magnetite-rich nodules formed by subsolidus oxidation of pre-existing kamacite-rich nodules. However, this model was rejected because of the lack of petrographic evidence for the factor-of-2 increase in molar volume expected when kamacite changes into magnetite [2]. It seems more likely that oxidation occurred in the nebula prior to chondrule formation. During chondrule melting, immiscible magnetite-rich melt droplets developed within the silicate droplet; in this particular chondrule, taenite with 71 wt.% Ni was the sole liquidus phase and developed euhedral morphologies as it crystallized. After the chondrule cooled below ~500°C the taenite transformed into awaruite.

Interplanetary dust particles (IDPs). M.E. Zolensky (personal communication, 1993) has observed rare unrecrystallized chondritic IDPs containing 0.01-0.03-μm-size euhedral kamacite grains associated with troilite (or pyrrhotite), and, in some cases, with enstatite, diopside, forsterite, feldspathic glass and/or amorphous pyroxene. Although some chondritic IDPs have been significantly reheated, the friability of the euhedral-kamacite-bearing assemblages suggests that they were not. It seems likely that these euhedral kamacite grains are nebular condensates that formed when the nebula cooled below 1063°C (the 50%-condensation temperature of Fe at 10^{-4} atm; [4]).

Vugs. Euhedral low-Ni kamacite grains occur within vugs in highly recrystallized Apollo 14, 15 and 16 lunar breccias [5]. Such grains exhibit trapezohedral, cubic, tetrahexahedral, octahedral and dodecahedral faces. They formed by vapor deposition of Fe onto silicate grain surfaces. An analogous case occurs in the Farmington L5 impact-melt breccia (and a few other ordinary chondrite breccias as well). Vugs within Farmington contain elongated prismatic and (probably) trapezohedral kamacite grains attached to a silicate substrate [6]. Calculations indicate that, after S, Fe is among the most abundant condensible vapor components in a gas generated by vaporization of lunar basalt or chondritic material [6,7]. This suggests that the Fe was probably derived from reduction of FeO in mafic silicates that were vaporized during shock events.

Ivanov [8] reported several 350-µm-size euhedral metallic Fe-Ni grains with 11.7-12.0 wt.% Ni, 0.54-0.68 wt.% Co and 0.63-0.68 wt.% P inside a 2-mm-diameter vug within the CR2-like lithology of Kaidun (i.e., Kaidun I). The vug itself is located within a fracture. The high Ni and Co contents of these euhedral metal grains place them close to the positively correlated Co-Ni trends of metallic Fe-Ni in CR chondrites [9]. Most CR metal grains with high Co and Ni probably formed in the nebula at low temperatures when metallic Fe reacted to form FeO or FeS [9]; however, the occurrence of the euhedral metal grains within a vug indicates that these grains probably condensed after an impact event caused vaporization of normal CR metal in the Kaidun regolith.

Lunar glass. Glass [10] reported the occurrence of about 25 ~4-µm-size octahedral crystals of kamacite with ~6 wt.% Ni situated along a plane within a 230-µm-diameter pale green glass spherule from Apollo 11 sample 10084. He also found similar octahedral metallic Fe-Ni crystals in two glass particles from sample 12057. Frondel *et al.* [11] reported 5-µm-sized octahedral crystals of metallic Fe in a glass fragment from Apollo 11 fines; isolated subhedral metallic Fe crystals reported in these fines may have been detached from glass surfaces. The relatively high Ni/Fe ratio in the metal reported by Glass [10] is similar to that in chondrites and, although not definitive, is consistent with the metal having been a meteoritic contaminant rather than having been formed by reduction of FeO from mafic silicates. It seems likely that these glass particles formed by impact melting lunar basaltic material and that the metal initially formed immiscible droplets. Von Engelhardt *et al.* [12] suggested that during cooling of the glasses the temperature remained near that of the crystallization temperature of Fe long enough to allow the growth of a single crystal from each immiscible metal droplet.

Impact-melt rock clasts. I report here the discovery of a 65x107 µm grain of euhedral tetrataenite (ordered FeNi) attached to a similarly sized grain of troilite within a 4x6-mm-size impact-melt rock clast in the Jelica LL6 chondrite breccia. The clast consists principally of olivine, orthopyroxene, diopside and plagioclase forming a hypidiomorphic-granular texture; minor phases include metallic Fe-Ni, troilite and chromite. After impact-melting, immiscible metallic-Fe-Ni-troilite droplets formed within the silicate melt. At ≥1200°C, while the surrounding silicate was still partly molten, taenite (the liquidus phase in many of the isolated metal-troilite droplets) began to crystallize. In one such droplet, taenite with ~50 wt.% Ni crystallized with a euhedral morphology. Troilite nucleated at one edge of this grain and began to crystallize at ~870°C. At ~460°C the taenite transformed into disordered FeNi; at 320°C the metal phase underwent an ordering reaction and formed tetrataenite.

A 60-µm euhedral metallic Fe-Ni grain found in the Sena H4 chondrite breccia [13] was also plausibly derived from an impact-melt rock clast.

References: [1] Housley R.M. (1981) *Proc. Lunar Planet. Sci. Conf.* **12B**, 1069-1077. [2] Rubin A.E. (1991) *Amer. Mineral.* **76**, 1356-1362. [3] Haggerty S.E. and McMahon B.M. (1979) *Proc. Lunar Planet. Sci. Conf.* **10**, 851-870. [4] Wasson J.T. (1985) *Meteorites: Their Record of Early Solar System History*, Freeman, New York. [5] Clanton U.S., McKay D.S., Laughon R.B. and Ladle G.H. (1973) *Proc. Lunar Sci. Conf.* **4**, 925-931. [6] Olsen E.J. (1981) *Meteoritics* **16**, 45-59. [7] Naughton J.J., Hammond D.A., Margolis S.V. and Muenow D.W. (1972) *Proc. Lunar Sci. Conf.* **3**, 2015-2024. [8] Ivanov A.V. (1989) *Geokhimya* no. **2**, 259-266. [9] Lee M.S., Rubin A.E. and Wasson J.T. (1992) *Geochim. Cosmochim. Acta* **56**, 2521-2533. [10] Glass B.P. (1971) *J. Geophys. Res.* **76**, 5649-5657. [11] Frondel C., Klein C., Ito J. and Drake J.C. (1970) *Proc. Apollo 11 Lunar Sci. Conf.*, 445-474. [12] Von Engelhardt W., Arndt J., Müller W.F. and Stöffler D. (1970) *Proc. Apollo 11 Lunar Sci. Conf.*, 363-384. [13] Jedwab J. (1972) *Meteoritics* **7**, 537-546.