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Magnetic domains and magnetic stability of cohenite from the Morasko iron meteorite

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ABSTRACT

Magnetic properties, texture and microstructure of cohenite grains from Morasko iron meteorite have been investigated using electron backscattered diffraction, Bitter pattern technique, magneto-optical imaging method and magnetic force microscopy. Cohenite shows much stronger magnetic contrast compared to kamacite because it is magnetically harder than the Fe-Ni alloy, and thus causes higher stray fields. A surprising result is the high stability and reversibility of the global stripe-like magnetic domain structure in cohenite when applying high magnetic fields up to 1.5 T, and exposing it to high temperatures above the Curie temperature of about 220 °C. Heating up to 700 °C under atmosphere conditions has shown that cohenite remains stable and that the global magnetic domain structures mainly recover to its preheating state. This observation suggests that magnetic domains are strongly controlled by the crystal anisotropy of cohenite. Branching magnetic domain structures at the grain boundary to kamacite can be annealed, which indicates that they are very sensitive to record deformation. EBSD observations clearly demonstrate that increasing deviation from the easy [010] crystallographic axis and stress localization are the main factors controlling the distortion of Bitter patterns, and suggest a high sensitivity of the cohenite magnetic domain structure to local microstructural heterogeneities. The results of this study substantiate the theory that cohenite can be a good recorder of magnetic fields in planetary core material.

1. Introduction

Microstructures and physico-chemical properties of iron meteorites present a window into the thermal and shock history in the early solar system (e.g [1]). Understanding of exotic magnetic phases like cohenite ($[\mathrm{Fe, Ni, Co}]_3\mathrm{C}$) provide a unique tool to decipher paleomagnetic signals and magnetic field records of early solar magnetic fields (e.g [2,3]). The Morasko iron meteorite, first found in 1914 near Poznan in Poland [4], contains ferromagnetic cohenite ($\mathrm{Fe_{2.95}Ni_{0.05}C}$) [5] either along interfaces of troilite and metal [6] or as oriented inclusions in the metal following the Widmanstätten pattern [7]. The Morasko meteorite is interpreted as a product of partial melting and impact events and as such it is classified as non-magmatic IIICD [8], a subgroup of the IAB group (e.g [9,10]). Neumann lines, which are reported to result from mechanical twinning at shock pressures >8 GPa [11] are ubiquitous (e.g [5,6]) and indicate a moderate shock metamorphic overprint.

According to Ringwood [12], the existence of cohenite indicates high pressure conditions in the meteorite. Lipschutz and Anders [13] noted that cohenite forms by exsolution from the solid state, during the cooling of an iron meteorite from 680 °C. However Brett [14] noted that cohenite indicates neither high nor low pressures but only a slow cooling in parent bodies between 650 and 610 °C. According to Wood [15] the $\mathrm{Fe_3C}$ stability field is large at high pressures suggesting coexistence with metallic liquid. As carbon is one of the light element candidates for the Earth's core, cohenite is suggested as a major inner core component [16]. Besides meteorites, cohenite is also described from inclusions in garnet (together with Fe-Ni and troilite) included in diamond from kimberlites [17], confirming its existence in the interior of the Earth.

The metallic ferromagnet cementite (synthetic form of natural cohenite) crystallizes in the orthorhombic structure with hexagonal close packed layers of iron with carbon filling the interstitial sites. Gao et al. [18] describes for a synthetic $\mathrm{Fe_3C}$ sample a magnetic transition from a low-pressure magnetic to a high-pressure non-magnetic phase above about 5.5 GPa similar to what is described for pyrrhotite [19]. Compared to all known meteorite magnetic minerals, cohenite exhibits very specific magnetic properties with a Curie temperature at 215 °C [20], which is nearly identical to the one reported for cementite about

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210 °C [21]. Sugiura and Strangway [20] additionally discovered that cohenite carries the more stable component of natural remanent magnetization of the Abee meteorite (enstatite chondrite) and, therefore may be a good recorder of magnetic fields in the early solar system. Cohenite is also the main magnetic remanence carrier of lunar Apollo Mare basalt 14053 [22], suggesting that it may be an interesting mineral for lunar paleomagnetism.

Cohenite displays very prominent stripe-like magnetic Bitter patterns [6]. It is well known that the Bitter pattern method provides a quick access to the local magnetic behavior of magnetic minerals and can also be used to localize internal stress in micrograins (see e.g [23,24]). Although Bitter patterns in cohenite have been known for a long time [25], this prominent magnetic behavior was not studied in detail in relation to crystallographic orientation and microstructure of cohenite grains in iron meteorites. Magnetic force microscopy (MFM) combined with electron backscattered diffraction (EBSD) measurements of globular cementite embedded in a ferrite matrix is reported in a metallurgical study of Batista et al. [26]. These authors found that the easy direction of magnetization in the orthorhombic cementite is the long [010] axis (a=5.09 Å, b=6.74 Å, c=4.52 Å). According to measurements of the saturation magnetization and crystallographic anisotropy of cementite as a function of temperature Blum and Pauthenet [27] suggested that the [001] axis is the easy axis of magnetization (which, in this case, is also the long axis of the unit cell). In uniaxial materials like the orthorhombic cementite/cohenite one axis is favored over the other two (hard) axis, which produce a strong anisotropy in these crystals. Blum and Pauthenet [27] report that cementite is a relatively hard magnetic material with high single crystal anisotropy constants ($K_1=118\times10^3$ Jm^{-3} and K_2 $=394\times10^3$ Jm^{-3}). Thus [010] is the easiest and [100] the hardest direction of magnetization. In terms of the nomenclature used in Batista et al. [26] and in our study, this corresponds to the b and a axis, respectively. To date, no information is available on the magnetic and thermal stability of the magnetic structure of natural cohenite.

We present in our study Bitter pattern, magneto-optical imaging (MOI) and magnetic force microscopy (MFM) results of cohenite from the Morasko meteorite and correlate this information with the crystallographic orientation and internal stress determined by EBSD measurements. The effect of an external laboratory magnetic field on the magnetic domain structure is studied using the MOI technique [28,29]. In order to understand the strong magnetic stability of cohenite we combined thermomagnetic measurements from room temperature to above the Curie transition with Bitter pattern and magnetic force microscopy imaging.

2. Sample description and analytical techniques

A description of the different phases of Morasko iron meteorite and their mineralogical composition is reported in detail elsewhere [6]. Briefly, it consists of a Fe-Ni alloy matrix (about 98 vol%) and troilite (FeS) nodules occupying about 2 vol%. The matrix is mainly composed of kamacite with α-Fe cell and less than 6% of Ni, and taenite with γ-Fe-cell and more than 20% Ni. Accessory minerals, mostly occurring in the margins of the troilite nodules, are schreibersite ($[Fe, Ni]_3P$), cohenite ($[Fe, Ni, Co]_3C$), sphalerite (ZnS), graphite (C), daubreelite ($FeCr_2S_4$) and silicate minerals (Na-pyroxene and plagioclase) [6]. Similarly to its metallurgical analogue cementite (Fe_3C), cohenite exhibits extraordinary corrosion/etching resistance and exceptionally high hardness. As a result, cohenite can be easy distinguished from schreibersite, kamacite, and taenite on polished surfaces [25].

Using a diamond saw, the sample from the interfacial area was cut in form of a small slab, embedded into epoxy resin and polished using diamond and alumina pastes. Optical microscopy (Leica Orthoplan microscope coupled with a Leica DFC 420C CCD camera) in reflected light was used to study the magnetic domain structure (uniformly magnetized region) using Bitter pattern technique. This technique is useful as it is sensitive to small variation in magnetization. For this purpose, the polished surfaces were coated with ferrofluid (EMG 807, Ferrofluidics GmbH) diluted with distilled water in the ratio 1:10.

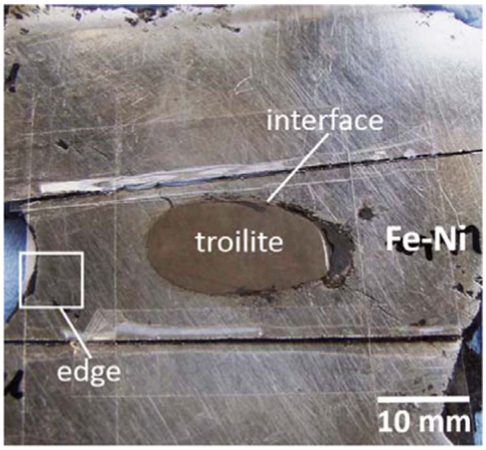

Fig. 1. An optical micrograph of the studied meteorite piece composed of troilite nodule surrounded by a Fe-Ni alloy. Two areas of interest are labeled - the interface and edge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The crystallographic texture was studied by electron backscattered diffraction (EBSD) using a Zeiss EVO MA 10 scanning electron microscope (SEM) (Zeiss AG, Germany) equipped with an EBSD pattern detecting system and the ESPRIT software (Bruker Nano GmbH, Germany) for data handling and analysis. The acceleration voltage was 20 kV, and probe current was 6 nA. The working distance between specimen and electron gun was 14 mm, and between specimen and EBSD detector it was 17 mm.

The effect of an external magnetic field on the magnetic domain structure of cohenite was investigated using magneto-optical (MO) imaging technique utilizing a Leica DM2500P microscope and a low-noise black and white CCD camera (Ikon-M, Andor Technology), as described in detail in previous studies [28,29]. The acquired MO images correspond to a saturation isothermal remanent magnetization state formed after applying a strong magnetic field (1.5 T). The magnetic field was imparted with a MMPM-9 (Magnetic Measurements Ltd.) pulse magnetizer.

Magnetic susceptibility as a function of temperature around the Curie transition of cohenite (~220 °C) was measured using an AGICO KLY-4S kappabridge (effective field intensity:300 A/m; frequency:=875 Hz). In order to reveal the effect of temperature cycles on the evolution of magnetic structures, a mini sample (about $2.5\times2.5\times4.5$ mm^3) containing high concentration of cohenite was cut from the meteorite using a diamond saw. Before and after temperature cycling, the polished sample surface coated with ferrofluid was studied with an optical microscope. The heating-cooling cycles were done in an argon atmosphere (flow rate of 110 mL min^{-1}) with a heating rate of 11°min^{-1}. The Curie temperature was calculated from the minimum in the first derivative curves while the transition width corresponds to the full width at half maximum (FWHM) of the derivative curves.

In-situ high-temperature observation of the magnetic domain structures was done using an Asylum Research MFP-3D magnetic force microscope (MFM). The MFM cantilevers are made from silicon or silicon nitride coated with CoCr. The MFP-3D collects high-pixel-density images (up to 5k×5k) with high-speed data capture up to 5 MHz. The heating-cooling runs around the Curie point of cohenite were done in air using temperature interval varying from 20 to 50 °C. The temperature was maintained to better than 0.2 °C precision with accuracy to 0.5 °C and temperature overshoots less than 0.2 °C.