Crystalline Structure, Stoichiometry and Magnetic Properties of the Morasko Meteorite

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The composition and structure of iron–nickel alloys smithereens extracted from the Morasko (Poland) Meteorite (fell ∼ 5 ka BP) were investigated by optical metallographic techniques, scanning electron microscopy and electron microprobe analysis, thermal analyses, magnetic measurements and X-ray diffraction. Microstructural analysis by scanning electron microscopy and optical microscopy has shown that the sample is composed from large grains of Fe–Ni alloy in which secondary phase crystals with well developed crystal habits and the size about 10 micrometers are distributed. Thermal analyses confirmed that the transformation from alpha to gamma Fe–Ni solid solution appearing as a function of temperature corresponds to about 5 wt% Ni in the Fe–Ni alloy. Possible scenario of the extraterrestrial sample solidification is related to the microstructural and magnetic behavior.

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1. Introduction

Around one tone of metallic extraterrestrial pieces of cosmic matter was found in the Morasko Meteorite Reserve (Poland) and its surrounding in about last hundred years. Moraska Góra (Morasko Hill) is the highest point in this part of Wielkopolska (Greater Poland Lowland), at around 154 m a.s.l. The variation of its topography is equaled by the variation in the rocks types of which inert strata and land surface is composed. At the surface more than 95% of these are Quaternary sediments of glacial and fluvioglacial origin — different in age but not younger than 18 ka BP (18000 years before present), belonging to the Poznań Stage of last glaciations. Only a small percentage of the surface consists of fine Neogene silts and clays of few millions of years old [1].

Metallic meteorites have been and still are discovered at Morasko close to the surface, normally up to the depth of 50 cm, not deeper that around 90 cm. It may indicate a fall of extraterrestrial matter on the surface of the ice cup and during the deglaciations located in the top part of glacigenic profiles. Practically it proved nevertheless a local impact, long time after the glacial landscape origin. Hot lamps of meteorite falling into the surface penetrated the unconsolidated Quaternary as well as Neogene sediments. The thermal influence of lamps on their immediate surroundings has been recorded in the zeroing of luminescence and creating the sinter-like coating. Later weathering resulted in the formation of a compact “meteorite skin”.

The performed radiometric dating proved that the metallic extraterrestrial matter fell over a wide area around the Morasko approximately about 5000 years ago. Apart of metallic meteorites, micrometeorites and magnetic spherules are also present. An explosive impact led to the creation of meteorite craters, too.

Our earlier studies (not published yet) have shown that the meteorite is composed to about 98 wt% of an (Fe,Ni)-alloy and to about 2 wt% of FeS nodules, up to 20 mm in diameter. The latter forms the host of different trace minerals, which are likewise the carriers of many trace elements. The principal Fe–Ni minerals are kamacite and taenite. FeS occurs as troilite, being often wrapped by rounded flakes of graphite. The trace minerals are represented by schreibersite, cohenite, sphalerite, and graphite. Additionally, tiny grains of daubreelite, altaite and silicate minerals were found, the latter being identified as the green Na-pyroxene cosmochlore (with probably composition NaCrSi$_2$O$_6$) and as plagioclase. Most of these trace minerals occur at the margins, but some within the troilite nodules.

2. Experimental

The structural composition and the microstructure of the samples was studied by analysis of X-ray diffraction (XRD) (Co $K_\alpha$) pattern, by scanning electron microscopy (SEM) and optical microscopy after polishing and etching in the solution 1 vol.% of hydrochloric acid in ethyl alcohol. Identification of present phases was carried
out with using back-scattered scanning electron images and energy dispersion analysis of X-rays (EDAX).

Phase transformations during heating and cooling were studied by a differential scanning calorimeter (DSC) in flowing argon at heating and cooling rate 20 °C/min. The magnetic properties were examined by vibrating sample magnetometer (VSM).

3. Results and discussion

3.1. XRD analysis

In Fig. 1 there is presented XRD pattern of sample in view. Phase analysis shown presence of bcc-(Fe,Ni) solid solution with unknown phase. The unit cell length for alpha-phase is \( a = 2.8735 \) Å and was determined by XRD analysis of (211) line. According to Pearson [2], quantity of Ni atoms in bcc-(Fe,Ni) solid solution may be more than 5 at.%. Quantity of Ni atoms was appreciated from comparison of measured unit cell length with FeNi solid solution values.

![XRD pattern of the meteorite sample.](image)

Fig. 1. XRD (Co Kα) pattern of the meteorite sample.

3.2. DSC investigations

In the DSC thermograms (Fig. 2) there can be seen two reversible peaks: first one under heating at 760 °C and at about 577 °C for cooling run, second one at 985 °C under heating and 950 °C cooling. The first process is most probably phase transition between \( \alpha \leftrightarrow \gamma \) phases. The second heat flow maxima may bring into correlation with XRD line at 36 degree, i.e. reversible transition of unknown phase with its high temperature modification.

3.3. Microstructure

The main body of the sample is formed by large single-phase grains (size of some millimeters). SEM observation after etching revealed that thin lamellas are present in the matrix grains (Fig. 3a,b). EDAX microanalyses showed that there is no difference in the composition of matrix and composition of lamellas (Table). Therefore, we suppose that these lamellas are ferrite (K8 lattice) and were formed from Fe/Ni austenite (K12 crystal lattice) during cooling through diffusionless transformation which is in agreement with the equilibrium Fe/Ni phase diagram.

![DSC thermograms with heating/cooling rate 20 °C/min.](image)

Fig. 2. DSC thermograms with heating/cooling rate 20 °C/min.: (a) heating, (b) cooling.

![Lamellas of ferrite in the austenitic grains (a) with melliniite crystals spread in the etched sample observed by SEM (b).](image)

Fig. 3. Lamellas of ferrite in the austenitic grains (a) with melliniite crystals spread in the etched sample observed by SEM (b). Melliniite crystal with dark-gray part seen under plane polarized light in polished sample (c). Melliniite phase is visible at the grain boundary between austenite grains (d).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Fe</th>
<th>Ni</th>
<th>P</th>
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<tr>
<td></td>
<td>wt%</td>
<td>at.%</td>
<td>wt%</td>
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<tr>
<td>austenite, ferrite</td>
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<td>93.6</td>
<td>6.8</td>
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<td>melliniite</td>
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<td>40.5</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td></td>
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TABLE

Elemental composition of phases presented in the meteorite by EDAX analyses.

In the inner parts of the grains, some secondary phase crystals with well developed habits can be seen (Fig. 3b). The elemental microanalysis of these crystal phase particles (Table) points out that they are Fe, Ni phosphides with composition close to melliniite (Ni,Fe)₄P [3] which
is a new mineral found in the Northwest Africa 1054 aca-
pucoite meteorite in 2005.

In plane-polarized reflected light, melliniite is dark-
gray (see Fig. 3c). These melliniite crystals are brittle. Observed cracks in the crystals obviously developed dur-
ing sample cooling due to different thermal expansion of the Fe/Ni matrix phase and melliniite crystals. Well de-
veloped habit planes confirm that melliniite crystals were formed in melted state e.g. the sample was formed by so-
lidification of the melt. The melliniite phase was also observed at the Fe/Ni grain boundaries (Fig. 3d).

3.4. Magnetic properties

The thermomagnetic dependences (Fig. 4a) reveal that during heating period the ferro-paramagnetic transfor-
mation occurs at 760°C. During the cooling of sam-
ple the transformation of overcooled gamma-phase into alpha-phase arises at 615–625°C (inflexed point of curve).

These values are in good congruence with results of DSC analysis. Such type of thermomagnetic curves is usually observed in Fe,Ni alloys with low content of Ni (from 1 to 10 at.%) [4]. According to the Fe/Ni phase di-
agram these temperatures answer the concentration of about 5 at.% of Ni in Fe–Ni alloy. The hysteresis loops in Fig. 4b show the different slopes represent the differ-
ent crystallographic orientation of the particular samples (grains about $3 \times 3 \times 1$ mm) to the magnetic field.

4. Conclusions

The famous Polish iron meteorite Morasko, and also those found in Przełazy and Jankowo Dolne near Gniezno, probably representing a single “meteorite rain”. We have confirmed in our study that the pieces of mete-
orite are Fe,Ni alloy in which a very rare mineral mel-
linite (NiFe)$_4$P was found in the form of small particles (tens of $\mu$m) spread in matrix of FeNi. Magnetic behavior is typical for FeNi solid solution.

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