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Microstructure of the Fermo meteorite

K. Iždinský([1]), G. Cevolani([3]), I. Kapišinský([2]), M. Zemánková([1]) and V. Porubčan([2])

([1]) *Institute of Materials and Machine Mechanics - 831 02 Bratislava, Slovakia*
([2]) *Astronomical Institute of the Slovak Academy of Sciences - 845 04 Bratislava, Slovakia*
([3]) *CNR-ISAC - Via Gobetti 101, 40129 Bologna, Italy*

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Summary. — Analyses by different electron microscopy methods contribute to draw the overall picture of the microstructure of the Fermo meteorite. Phase composition obtained by Scanning Electron Microscopy (SEM) may provide useful information about the origin of previously reported phases including kamacite, taenite, troilite, enstatite, silicate particles of olivine and pyroxene groups. The morphological aspects of separate micro- and nano-structural constituents revealed by Transmission Electron Microscopy (TEM) may reflect transformations that contribute to reconstruct the events affecting the true history of the cosmic body. Achievements of very fine-grained microstructure of minerals investigated by TEM micrographs and ion milling analysis are approaching current nanotechnology efforts.

PACS 96.30.Za – Meteors, meteorites and tektites.
PACS 95.85.Nv – X-ray.

1. – Introduction: Description of the event and recent studies

On September 25, 1996 a stony meteorite fell in central Italy at a site (13° 45′ 12″ E, 43° 10′ 52″ N) close to a field, 3-4 km north-east of the town of Fermo and a few kilometres from the Adriatic coast [1,2]. The event took place during daylight (17:30 UT) and the fireball was travelling south-southeast. The meteorite was recovered as a single stone on a wet and soft clay bedrock within a crater of 30–40 cm and now is housed at the Polar Museum of Villa Vitali in Fermo. So far, only a few meteorites have been recovered for which detailed data on atmospheric trajectory and orbit exist. As it was a daytime bolide, a rough reconstruction of the true fall path of the meteorite through the Earth's atmosphere was allowed by eye-witness accounts [3].

Stony meteorites are well represented by the very numerous chondrites, which most closely approximate primitive solar nebula condensates and contain spherical micro-millimetre- to millimetre-sized chondrules that rapidly melted and immediately cooled early in the Solar System's history [4]. Objects responsible for bright fireballs from which

Fig. 1. – Meteorite Fermo, housed at the Polar Museum of Villa Vitali in Fermo.

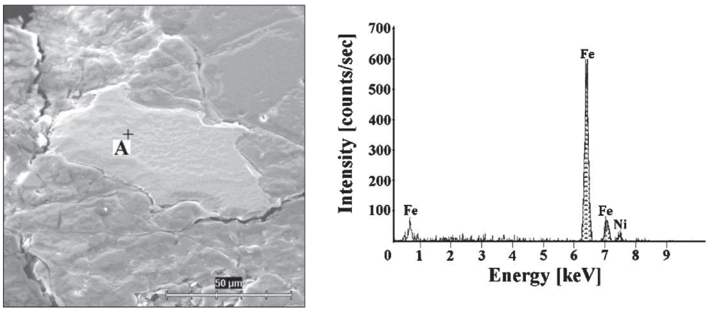

Fig. 2. – Kamacite particle in the microstructure of Fermo meteorite (secondary electron micrograph)—left. EDX spectrum obtained from point A (energy dispersive X-ray spectroscopy)—right.

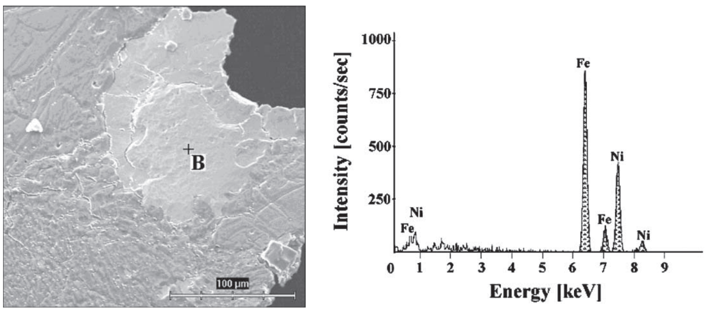

Fig. 3. – Taenite particle in the microstructure of Fermo meteorite (secondary electron micrograph)—left. EDX spectrum obtained from point B (energy dispersive X-ray spectroscopy)—right.

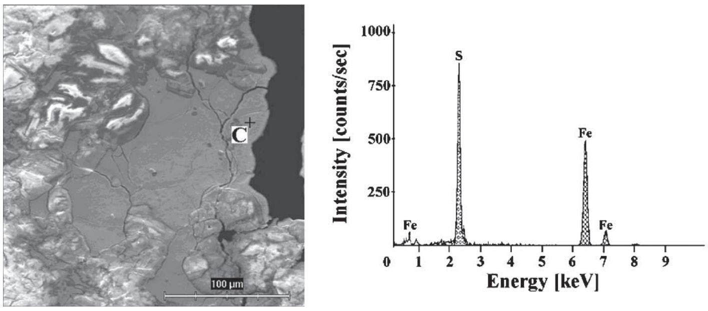

Fig. 4. – Troilite particle in the microstructure of Fermo meteorite (secondary electron micrograph)—left. EDX spectrum obtained from point C (energy dispersive X-ray spectroscopy)—right.

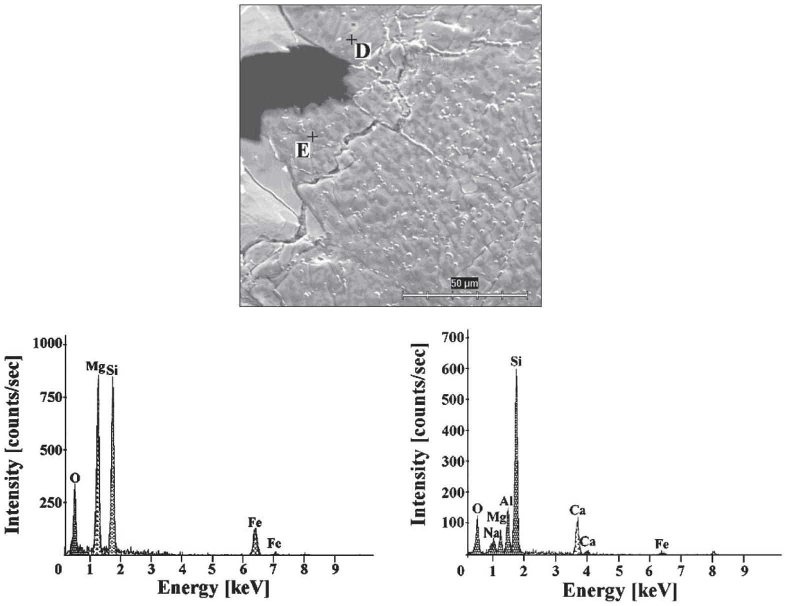

Fig. 5. – Silicate particles in the microstructure of Fermo meteorite (secondary electron micrograph)—top. Energy dispersive X-ray spectroscopy spectrum obtained from point D (left) and point E (right).

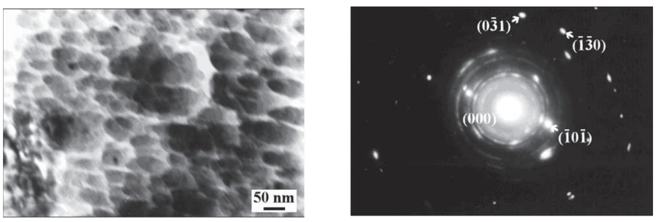

Fig. 6. – Fine-grained microstructure of kamacite particle (TEM micrograph, bright field image)—left. SAED pattern corresponding to the zone of α-Fe (selected area electron diffraction)—right.

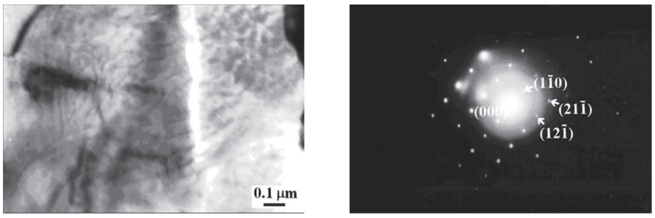

Fig. 7. – Fine-grained microstructure of olivine particle (TEM micrograph, bright field image)—left. SAED pattern corresponding to the zone of orthorhombic olivine (selected area electron diffraction)—right.

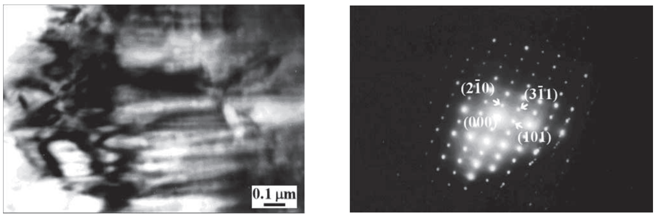

Fig. 8. – Fine-grained microstructure of enstatite particle (TEM micrograph, bright field image)—left. SAED pattern corresponding to the zone of orthorhombic enstatite (selected area electron diffraction)—right.

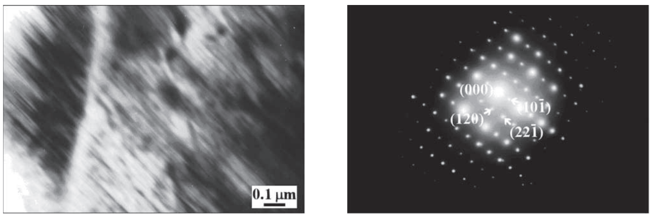

Fig. 9. – Fine micro-lamellar plagioclase particle (TEM micrograph, bright field image)—left. SAED pattern corresponding to the zone of triclinic plagioclase (selected area electron diffraction)—right.

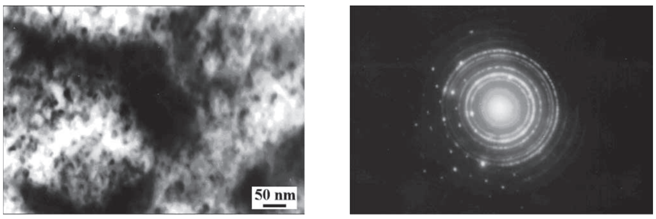

Fig. 10. – Fine-grained microstructure of troilite particle (TEM micrograph, bright field image)—left. SAED pattern corresponding to random orientation of hexagonal troilite grains (selected area electron diffraction)—right.

meteorites may drop occupy the low-mass end of the asteroid size spectrum. Fermo is the 12th meteorite found in Italy in the last century, but is the third most important in terms of weight, after Vigarano (a carbonaceous chondrite of two pieces, 11.5 kg and 4.5 kg, recovered in 1910) and Bagnone (an iron body of 48 kg found in 1904) [5].

The stone (size $19 \times 24 \times 16$ cm), weighing 10.2 kg, has an irregular, angular, prismatic shape with rather sharp corners (fig. 1). It was almost completely covered by a very thin black fusion crust. Depressions similar to thumb prints (regmaglypts) are evident on two faces of the stone. After about twenty days after the fall a 2–3 cm thick slab (weight 800 g) was cut for the detection of cosmogenic nuclides at the Istituto di Cosmogeofisica del CNR and Dipartimento di Fisica Generale dell' Università di Torino [6].

The presence of solar flares as well as neutron capture effects in the isotopic composition of rare gases acquired on its parent body based on the measurements of tracks, rare gases and radionuclides, was demonstrated and in addition, the galactic cosmic-ray exposure age was determined to be 8.8 Ma by Bonino *et al.* [6]. Activities of a dozen radionuclides ranging in half life (from 16 day ^{48}V to 0.73 Ma ^{26}Al) are consistent with their expected production rates. Track, rare gas and radionuclide data show that the meteoroid was a small body (≤ 120 kg) and had a simple, one stage exposure history to cosmic rays in the interplanetary space. The presence of solar gases and the neutron capture effects indicate several stages of irradiation on the parent asteroid.

More recently, Orlicky *et al.* [7] investigated the dominant carriers of the remanent magnetism (RM) and basic magnetic properties of Fermo. Hvozdara *et al.* [8] performed a study of heat diffusion from the surface of the meteorite into its interior as a possible assessment of an origin of the RM. In these last years, Kapisinski *et al.* [9,10] performed supplementary investigation on some magnetic properties carried out by the temperature-dependent measurements of the initial magnetic susceptibility, remanent magnetization and coercive force of two samples of Fermo individually placed into high vacuum.

In the present paper investigation of some aspects of the microstructure of the Fermo meteorite is presented and discussed by utilizing electron microscopy analysis.

2. – Motivation

As already shown in previous papers [9,10] the microstructure of the Fermo meteorite is formed by a mixture of heterogeneous phases on a micrometric scale. Whereas the overall phase composition provides useful information regarding the origin of particular component particles, the morphology of separate microstructural constituents may reflect the transformations that had taken place within the active life of the meteorite. The knowledge of these transformations may significantly contribute to more precise reconstruction of events affecting the true history of the stony cosmic body.

As far as the morphology of phase appearance is concerned, electron microscopy provides quite unique information complementary to the more widespread examination techniques of the geological structure. This is exceptionally important when the particle or grain sizes appear in the micro- or even nano-scale ranges. In this case, the capability of available electron microscopy analytical techniques is quite effective.

The limitations of these techniques are related predominantly to the sample size. In the case of Scanning Electron Microscopy (SEM) relative large samples can be studied and the overall picture of the studied properties can be obtained. However in the case of Transmission Electron Microscopy (TEM), the examined area is limited to the narrow region previously thinned to transparency and the obtained information is limited to this particular location. Therefore it may well appear that in the case of a large structural inhomogeneity, *e.g.*, in the meteorite macrostructure, quite discrepant information from different sample regions can be obtained.

3. – Experimental material and procedure

A thin plate from an approximately 1 cm^3 large piece of the Fermo meteorite was cut by a precise diamond saw for structural studies. About 3 mm large particle detached from the thin plate was subsequently used for the TEM sample preparation.

The meteorite sample was embedded into a brass ring with the outer diameter of 3 mm using a one component glue ARALDIT AT 31. This sample was then mechanically thinned from both sides down to the thickness of about 80 micrometers. Further thinning was performed by argon ion bombardment down to the electron beam transparency. A small hole appeared in the central part of the sample after about 60 hours of careful bombardment using 7.5 kV and 1 mA argon ion beam inclined at 8° to the surface.

SEM observations were performed using the JEOL 5310 electron microscope operated at the accelerating voltage of 15 kV, TEM observations were carried out at the JEOL JEM 100 C analytical electron microscope operated at 100 kV. EDX analyses were performed using a KEVEX DELTA class IV spectrometer with an ultra-thin window detector. Ion milling was completed using BAL-TEC RES 010 equipment.

4. – Results

SEM observations with EDX analyses confirmed the presence of previously reported phases also in the currently examined region. Kamacite, taenite, troilite and silicate particles of olivine and pyroxene groups are shown with corresponding EDX spectra in figs. 2 to 5. Nickel-iron metals and troilite (FeS) form particles of predominantly irregular shapes, some tens of micrometers large. These particles appear mostly in the matrix formed by different silicate phases. Numerous cracks seen in the figures underline the brittle character of the meteorite structure making the sample preparation extremely difficult and time consuming.

The substantial contribution of this work is the achievement of some microstructural data related to the observed region. Microstructure of kamacite confirmed by the corresponding electron diffraction pattern is shown in fig. 6. As can be seen in the TEM bright field image, the structure is formed by mostly globular grains with the mean size of about 50 nm. This can be recognized as very fine-grained microstructure approaching the world of current nanotechnology efforts.

The microstructure of olivine shown in fig. 7 also reveals fine grains with the size range below 100 nm. Fine grains exhibit no preferential orientation indicating relative uniform cooling from the melting temperature.

Grains displaying mostly elongated shapes can be seen in the enstatite particle shown in fig. 8. The size grain is slightly larger than in previous examples.

Plagioclase particle shown in fig. 9 displays a fine lamellar structure. The lamellae are unidirectionally oriented with a large length-to-thickness ratio.

Troilite particle in fig. 10 exhibits no characteristic structural features. With respect to the corresponding electron diffraction ring pattern it is formed by numerous fine grains with random orientation.

5. – Concluding remarks

In the present analysis of the microstructure of the Fermo meteorite, usual mineral phases including kamacite, taenite, troilite, enstatite and olivine were identified. Each phase has a different microstructure reflecting its chemical composition and conditions of origin as well as possible chemical and mechanical interactions with the environment.

It would be very interesting and useful to compare the microstructures obtained also from other regions of the meteorite. The grain size and shape might indicate the cooling rates as well as possible collisions or impingement effects of molten primary particles. The microstructure of surface or subsurface regions should reflect the transformations related to the meteorite interaction with the Earth's atmosphere.

As shown in the presented study, structural analysis performed by TEM (Transmission Electron Microscopy) can significantly contribute to the overall picture of the meteorite microstructure. While the SEM (Scanning Electron Microscopy) observations reveal the structure with typical chemical composition, the TEM analysis reveals the morfology and completes the phase identification. Moreover, it can well distinguish between an amorphous or crystalline structure of present phases.

The crucial point here is the proper choice of sample preparation technique for TEM observations. This is a quite demanding task, due to the presence of multiple phases with quite different structure and properties. The ion milling adopted in this work has fully proved its potential in simultaneous thinning of metallic, oxide and intermetallic phases yielding wide transparent areas of investigated samples.

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