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Microstructural Characterization of Reheated Iron Meteorites by Electron Microscopy Techniques

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Iron meteorites are Fe-Ni alloys and are thought to come from the metallic cores of asteroids. Most iron meteorites have a Widmanstatten structure of low Ni bcc kamacite in a matrix of high Ni fcc taenite. This microstructure formed during slow cooling inside parent asteroidal bodies and was not destroyed during asteroidal break-up or entry through the Earth's atmosphere. The Ni gradients produced during the formation of the Widmanstatten pattern can be used to measure the cooling rate of the meteorite in its parent body in a temperature range from 1000 K to 500 K. A small number of iron meteorites have been damaged by heavy shock and subsequent reheating or even remelting in their parent bodies or during the process of asteroidal break-up. In some cases iron meteorites have been reheated on earth, for example by blacksmithing. Here we used SEM, EBSD, AEM and EPMA to characterize the microstructure in several reheated iron meteorites and computer simulation to measure cooling rates or reheating temperatures.

Figures 1a,b show EBSD color maps of the crystallographic orientations of fcc and bcc phases in a Babb's Mill (Troost's Iron, 17.05 wt% Ni, 0.13 wt% P). The black areas which are not indexed and located between fcc and bcc grain boundaries are very likely phosphide, as shown in the EPMA x-ray map (Fig.1c). The EBSD and EPMA results indicate that the original micro-structure has disappeared and a recrystallized microstructure has formed. The recrystallization process leading to the formation of the observed microstructures was caused by an impact-induced shock event. The shock level can be estimated indirectly at more than ~75 GPa since this shock level is required for recrystallization of meteoritic irons under laboratory conditions [1]. The recrystallization temperature is about 450^0 C, which is very close to the reported recrystallization temperature of pure iron of 450^0 C [2].

The cooling rate of an iron meteorite after shock reheating can be calculated by measuring the taenite Ni profile which develops during the cooling process. Figure 2a shows the Ni distribution measured by AEM in a 1 μm^2 area of a FIB thin section in the Fuzzy Creek iron (12.4 wt% Ni, 0.18 wt% P). The measured taenite Ni profile across a kamacite/taenite/kamacite region (Fig.2a) was used to estimate a cooling rate of 0.5 K/yr by comparison with a calculated Ni profile (Fig 2b).

Blacksmiths have reheated iron meteorites to make various tools. While all of Babb's Mill meteorites (Troost's Iron) were reheated by impact on the parent asteroid, some pieces of Babb's Mill (Troost's Iron) were forged by a blacksmith after its fall. Blacksmiths commonly use a forging heat in the yellow-orange color range (~1300-1500 K). The kamacite (bcc) and taenite (fcc) of the Babb's Mill (Troost's Iron), Fig. 1, were reheated to this temperature range and the microstructure in Fig.1 went through a dissolution process. The Ni, Co, P and other elements began to homogenize towards the average composition of Babb's Mill (Troost's Iron). Figure 3 shows the measured Ni profile obtained by EPMA in a Babb's Mill iron reheated by a blacksmith. Calculated Ni profiles for dissolution at three temperatures between 1300 and 1500 K were chosen to see how long it would take to change the Ni profile of the Babb's Mill (Troost's Iron) meteorite (Fig. 1) to match the measured profile. Reheating by the blacksmith is bracketed between 5 minutes at 1500 K to 180 minutes at 1300 K.

References
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[2] Mitchell B. S. *An Introduction to Materials Engineering and Science: For Chemical and Materials Engineers.* Wiley-Interscience, 1st edition, Hoboken, NJ, 2003.
[3] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy (DOE) under contract DE-AC04-94AL85000.

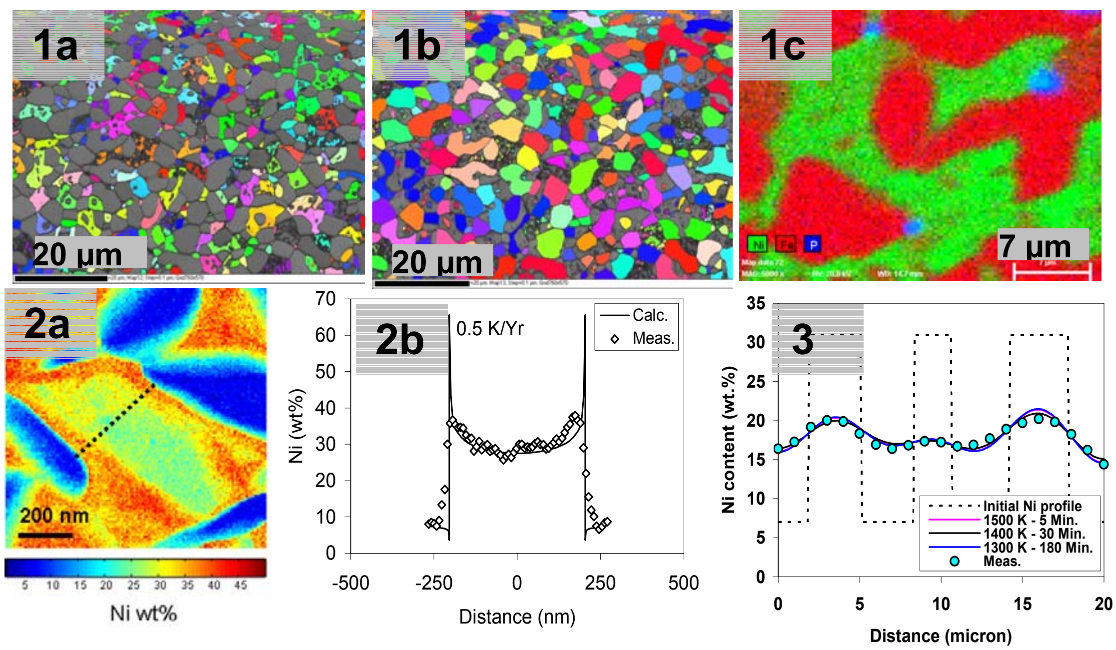

Fig.1a and b. EBSD images of the fcc and bcc phases in reheated Babb's Mill (Troost's Iron), sample ASU 2905. Fig. 1c. EPMA X-ray map of Ni, Fe and P. Fig. 2a Ni variation in a 1 μm^2 area of the Fuzzy Creek iron meteorite. Fig. 2b. Calculated and measured Ni variation across a kamacite/taenite/kamacite area in Fuzzy Creek. A calculated cooling rate of 0.5 K/yr gives a Ni profile which matches the measured Ni profile. Fig. 3. Comparison between the measured and calculated Ni profile in the Babb's Mill iron for dissolution of kamacite and taenite when the meteorite was reheated by a blacksmith.

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