Abstract—Cooling rate experiments were performed on P-free Fe-Ni alloys that are compositionally similar to ordinary chondrite metal to study the taenite → taenite + kamacite reaction. The role of taenite grain boundaries and the effect of adding Co and S to Fe-Ni alloys were investigated. In P-free alloys, kamacite nucleates at taenite/taenite grain boundaries, taenite triple junctions, and taenite grain corners. Grain boundary diffusion enables growth of kamacite grain boundary precipitates into one of the parent taenite grains. Likely, grain boundary nucleation and grain boundary diffusion are the applicable mechanisms for the development of the microstructure of much of the metal in ordinary chondrites. No intragranular (matrix) kamacite precipitates are observed in P-free Fe-Ni alloys. The absence of intragranular kamacite indicates that P-free, monocrystalline taenite particles will transform to martensite upon cooling. This transformation process could explain the metallography of zoneless plessite particles observed in H and L chondrites. In P-bearing Fe-Ni alloys and iron meteorites, kamacite precipitates can nucleate both on taenite grain boundaries and intragranularly as Widmanstätten kamacite plates. Therefore, P-free chondritic metal and P-bearing iron meteorite/pallasite metal are controlled by different chemical systems and different types of taenite transformation processes.

INTRODUCTION

Fe-Ni metal composed of taenite (γ, face-centered-cubic) and kamacite (α, body-centered-cubic) is present in varying amounts in ordinary chondrites, stony-iron, and iron meteorites. The metallography of meteoritic metal can be used to infer the thermal and physical history of meteorites and their asteroidal parent bodies.

Most meteoric metal cooled from temperatures within the single-phase taenite field (Fig. 1) at rates of 1–100°C/Myr (Wood 1964; Wood 1967; Goldstein and Short 1967; Willis and Goldstein 1981). In most iron and pallasite meteorites, a Widmanstätten structure consisting of kamacite plates aligned along the octahedral planes of the taenite matrix is produced during cooling.

Type 4–6 ordinary chondrites experienced metamorphic heating to peak temperatures between 700 and 900°C (McSween et al. 1988). At these temperatures, chondritic metal lies within the single-phase taenite field (or within the 2-phase taenite + troilite [FeS] field) (see Fig. 1). The taenite transformations, which occurred upon cooling, are commonly assumed to have been controlled by the same mechanism as iron meteorites, i.e., by kamacite nucleation and growth within a taenite matrix (Wood 1967). However, important metallographic differences between iron meteorites and ordinary chondrites cast doubt on this assumption:

1. Iron meteorite microstructures developed from single taenite crystals that are commonly >1 m across. Ordinary chondrite metal occurs as 1 µm- to 1 mm-sized metal troilite assemblages that are peppered throughout a matrix of olivine and pyroxene. Most of the metal microstructures in ordinary chondrites developed from taenite particles that contain 1 or more grain boundaries (polycrystalline taenite).

2. Most iron meteorites exhibit a well-developed Widmanstätten structure. Widmanstätten structure is rarely observed in ordinary chondrites, and taenite/kamacite interfaces are typically non-planar.

3. Iron meteorites contain up to 2 wt% P in alloy solid solution and as phosphide precipitates (Buchwald 1975). Ordinary chondrite metal contains <0.002 wt% P (Reed 1964).

Ternary Fe-Ni-P alloy cooling experiments have been used to investigate taenite transformations in P-bearing iron
and pallasite meteorites (Doan and Goldstein 1969; Goldstein and Doan 1972; Narayan and Goldstein 1984a, b). These experiments provide information about phase precipitation sequences and kamacite nucleation sites in iron and pallasite meteorites. Unfortunately, the Fe-Ni-P alloy cooling experiments are not useful for understanding the phase transformations that occurred in P-poor ordinary chondrite metal.

In this study, P-free Fe-Ni alloy cooling experiments were performed to study the taenite → taenite + kamacite reaction in alloys that are compositionally similar to ordinary chondrite metal. Alloys were cooled from the taenite field into the taenite + kamacite field to identify the sites of kamacite nucleation and to describe the kamacite growth process. The cooling experiments investigated the effects of adding Co and S to P-free Fe-Ni alloys and the roles of interfaces such as taenite/taenite grain boundaries.

The experiments provide information about the taenite transformations that occurred in ordinary chondrites as they cooled from peak metamorphic temperatures. The influence of taenite grain boundaries, which are common in ordinary chondrite metal but rare in iron meteorite metal, is investigated. The results of the cooling experiments provide a basis for interpreting ordinary chondrite metal microstructures and for understanding metallographic differences between ordinary chondrites and iron meteorites. The application of the experimental results to understanding ordinary chondrite metallography is discussed in detail in a companion paper (Reisener and Goldstein 2003).

**EXPERIMENTAL PROCEDURE**

**Alloy Preparation**

Two binary Fe-Ni alloys (alloys A1 and A2) and 2 Fe-Ni alloys (alloys A3–A4) containing variable amounts of Co and S were prepared to simulate ordinary chondrite metal (Table 1). The metal fraction of each alloy contains approximately 9 wt% Ni, typical of metal particles in H chondrites and in many iron meteorites. The alloys were prepared from high purity elements (purities >99.99 wt%) and contained ≤0.0015 wt% C. The pure elements were melted in a fused quartz melting chamber using a Lepel 30 kW high frequency induction furnace. The melting chamber was flushed with Ar-H₂ gas during melting to prevent alloy oxidation and to suppress evaporative loss of volatile S. The molten metal was held in the liquid state for 1–2 min to ensure complete homogenization and was then cooled to room temperature.

**Alloy Heat-Treatment**

Each ingot of approximately 5 g was placed in an alumina crucible, wrapped in tantalum foil, and vacuum-encapsulated inside a fused quartz capsule. The Ta foil getters oxygen and protected the alloys from Si vapor that was liberated from the quartz capsules during heat-treating. The vacuum-encapsulated alloys were heat-treated in horizontal tube furnaces (Applied Test Systems).

Alloy A1 (Fe-9Ni) was homogenized within the single-phase taenite field at 1100 ± 5°C for 20 days to eliminate elemental zoning formed during solidification. The alloy was cooled to the equilibrium kamacite precipitation temperature of 700°C over the course of 1 day and then cooled through the taenite + kamacite field at a rate of 4°C/day. At 500°C, the
alloy was removed from the furnace and quenched in liquid nitrogen.

Alloys A2–A4 were heat treated at 900°C for 20 days to homogenize the alloys while avoiding eutectic melting in the sulfur-bearing alloy A4. The homogenization temperature placed alloys A2 and A3 within the single-phase taenite field, while the S-bearing alloy A4 was within the 2-phase taenite + troilite field. After homogenization, the alloys were cooled to the equilibrium kamacite precipitation temperature of approximately 700°C over the course of 1 day and then cooled from 700 to 550°C at a rate of 3°C/day. At 550°C, alloys A2–A4 were removed from the furnace and quenched in liquid nitrogen.

The final heat-treatment temperature (500°C for alloy A1, 550°C for alloys A2–A4) was chosen so that the martensite phase transformation was not initiated during slow furnace cooling. The final furnace temperatures were at or above the Fe-9Ni martensite start temperature of ~500°C (Kaufman and Cohen 1956) (see Fig. 1), ensuring that any experimentally grown kamacite precipitates formed directly from taenite by the taenite → taenite + kamacite reaction. Residual taenite did transform to martensite, however, when the alloys were removed from the furnace and quenched in liquid nitrogen.

Analytical Procedures

The heat-treated alloys were mounted in epoxy and polished with diamond paste from 15 µm down to 0.06 µm using standard metallographic techniques. The samples were etched with Nital (2 vol% HNO₃, balance ethyl alcohol) for 20–60 sec to reveal fine-scale metal microstructures. Metal microstructures were characterized using optical microscopy and scanning electron microscopy (JEOL 5410 SEM). After microstructural characterization, the alloys were repolished to ensure that interphase interfaces were flat for subsequent electron probe microanalysis.

The alloys were analyzed for Fe, Ni, Co, and S using a Cameca SX50 electron microprobe operated at accelerating voltages of 15 or 20 kV, a beam current of 15–20 nA, and counting times of 30–50 sec. Iron, Ni, and Co data were calibrated using pure elements. Sulfur was calibrated using troilite from the Grant iron meteorite. X-ray intensities were reduced to composition using the ϕ(ρz) PAP calculation process.

RESULTS

Microstructures

The matrix of the 4 P-free alloys consist primarily of blocky to lath structured martensite, which formed when the alloys were removed from the furnace and quenched in liquid nitrogen. Although taenite is no longer present, the original taenite grain boundaries are marked by boundaries where martensite lathes terminate (Figs. 2a–5a). In the binary Fe-Ni alloy A1 (homogenized at 1100°C), the parent taenite grains were relatively equi-dimensional with an average diameter of ~50 µm. The parent taenite grains in alloys A2–A4 (homogenized at 900°C) were substantially smaller, 10–20 µm across, due to less extensive taenite grain growth at the lower homogenization temperature.

Alloy A1 contains approximately 1 vol% kamacite, which occurs as 5–10 µm thick precipitates along taenite grain boundaries (Fig. 2). Kamacite precipitates that formed at taenite/taenite boundaries tend to be lens-shaped, are spaced irregularly along the original taenite grain boundaries, and cover a relatively small fraction of the total taenite grain boundary area (Fig. 2a). Kamacite precipitation also occurred...
at many taenite triple junctions and at most taenite grain corners (Fig. 3a). The kamacite precipitates that formed at taenite triple junctions and taenite grain corners are generally larger than those that formed at taenite/taenite boundaries. Alloys A2 (binary Fe-Ni) and A3 (ternary Fe-Ni-Co) contain ~3 vol% kamacite, which is present as 5–20 µm thick grain boundary precipitates that have equi-dimensional shapes and have consumed large portions of the original taenite grains (Fig. 4a).

An optical micrograph of the Fe-Ni-Co-S alloy A4 is shown in Fig. 5a. The microstructure is characterized by 5–20 µm rounded blebs and branching networks of troilite surrounded by taenite grains that are 10–20 µm across. The metal fraction contains ~4 vol% kamacite as equi-dimensional, 5–20 µm-thick grain boundary precipitates. These kamacite precipitates are commonly contiguous with both taenite and troilite and abut troilite blebs that appear to be isolated from each other in the plane of sectioning (Fig. 5a). In some cases, kamacite precipitates completely surround troilite blebs in the plane of sectioning (swathing kamacite) (Fig. 5a).

Fig. 3. a) Optical photomicrograph of alloy A1 showing 2 kamacite precipitates that formed at taenite triple junctions; b) microprobe Ni traverse across the taenite/taenite boundary showing a Ni increase at the boundary.

No intragranular (matrix) kamacite precipitates, such as Widmanstätten kamacite needles, were observed in any of the P-free alloys A1–A4.

Phase Compositions

The Ni and Co compositions of the original taenite grains (now martensite) in alloys A1–A4 are reported in Table 2. These compositions reflect the parent taenite composition established during alloy synthesis/homogenization. In each alloy, the interiors of the original taenite grains are homogeneous within microprobe counting statistics at the 95% confidence level (Figs. 2–5).

Taenite Ni enrichments of 1–2 wt% are commonly measured at flat taenite/kamacite interfaces where kamacite nucleation presumably occurred (i.e., at an original taenite/taenite grain boundary) but not at curved taenite/kamacite interfaces that represent advancing kamacite growth fronts (Fig. 2). Taenite Ni enrichments are also measured at taenite/
Fe-Ni taenite cooling experiments

The small troilite precipitates probably formed during cooling as S exceeded solubility limits in taenite (Ma et al. 1998).

The kamacite precipitates in the binary Fe-Ni alloys A1 and A2 contain 4.8 and 4.6 ± 0.1 wt% Ni, respectively (Table 2; Fig. 2b). Within a given alloy, the kamacite precipitates are homogeneous both within and between the kamacite grains, as limited by microprobe counting statistics (Fig. 2b).

In the Co-bearing alloys A3–A4, kamacite precipitates contain 4.7 ± 0.1 wt% Ni and 0.60–0.75 wt% Co (Table 2; Figs. 4b and 5b). The Co partitioning between taenite and kamacite is consistent with phase equilibria in the Fe-Ni-Co system, which shows that kamacite Co concentrations are higher than taenite Co concentrations at all temperatures (Widge and Goldstein 1977).

**DISCUSSION**

**Phase Transformations in the P-Free Alloys A1–A4**

**Nucleation of Kamacite**

The P-free alloys A1–A4 were homogenized at temperatures of taenite stability and subsequently cooled to temperatures where taenite and kamacite coexist in equilibrium. Kamacite did not nucleate within the taenite single crystal matrix. Kamacite, however, nucleated at taenite/taenite boundaries, at taenite triple junctions, and at taenite grain corners. The precipitation process was taenite → taenite + kamacite. The taenite grain boundaries were energetically favorable sites for heterogeneous kamacite nucleation because they effectively decreased ΔG, the total energy change that occurs during nucleation. Aaron and Aaronson (1968) pointed out that grain boundary nucleation is especially important during fcc → bcc transformations (for example, the Fe-Ni system taenite → taenite + kamacite transformation) because fcc/bcc interfaces are lower energy than fcc/fcc interfaces. Before the present Fe-Ni alloy cooling experiments, the important role of taenite grain boundaries as kamacite nucleation sites was not recognized.

Alloys A2–A4 had a higher density of taenite grain boundaries than alloy A1, and therefore, more sites for heterogeneous kamacite nucleation were available, resulting in widespread kamacite grain boundary precipitation. The S-saturated alloy A4 contains the largest fraction of kamacite precipitates. In this alloy, kamacite precipitation may have also been aided by heterogeneous nucleation at taenite/troilite interfaces.

**Growth of Kamacite Grain Boundary Precipitates**

Using alloy compositions and cooling rates that apply to alloys A1–A4, computer simulations based on the Hopfe and Goldstein (2001) metallographic cooling rate program show that kamacite plates should be ~0.2 µm thick if growth occurs by volume diffusion. The kamacite grain boundary precipitates that formed in alloys A1–A4 are, however, 5–

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**Figure 5.** a) Optical photomicrograph of alloy A4 showing textural relationships between taenite (T), kamacite (K), and troilite (FeS); b) microprobe Ni traverse across taenite/kamacite and kamacite/troilite interfaces.

**Table 2.** Measured alloy compositions.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Taenitea Ni (wt%)</th>
<th>Taenitea Co (wt%)</th>
<th>Kamacite Ni (wt%)</th>
<th>Kamacite Co (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 (Fe-9Ni)</td>
<td>9.5 ± 0.1</td>
<td>–</td>
<td>4.8 ± 0.1</td>
<td>–</td>
</tr>
<tr>
<td>A2 (Fe-9Ni)</td>
<td>9.1 ± 0.1</td>
<td>–</td>
<td>4.6 ± 0.1</td>
<td>–</td>
</tr>
<tr>
<td>A3 (Fe-9Ni-0.5Co)</td>
<td>8.9 ± 0.1</td>
<td>0.45 ± 0.04</td>
<td>4.7 ± 0.1</td>
<td>0.60–0.75</td>
</tr>
<tr>
<td>A4 (Fe-8Ni-0.5Co-2S)</td>
<td>9.1 ± 0.1</td>
<td>0.45 ± 0.04</td>
<td>4.7 ± 0.1</td>
<td>0.60–0.70</td>
</tr>
</tbody>
</table>

aCore.
20 µm thick. Clearly, the experimentally grown kamacite precipitates are orders of magnitude too large to have formed by volume diffusion alone. The fact that Ni is enriched at taenite/taenite grain boundaries (Figs. 3b and 4b) indicates that the growth of kamacite grain boundary precipitates is associated with grain boundary diffusion.

Fast diffusion along metal grain boundaries is well-established as contributing to the growth of grain boundary precipitates. The general mechanism of grain boundary precipitate growth was studied by Aaron and Aaronson (1968), who proposed a multiple step process for precipitate growth, involving: 1) slow atom diffusion through the matrix lattice to grain boundaries; and 2) fast atom diffusion along the grain boundaries toward the growing precipitates.

Applying the Aaron and Aaronson (1968) model to Fe-Ni alloys, taenite grain boundaries apparently act as collector plates that funnel Ni away from the growing kamacite grain boundary precipitates (Fig. 6), resulting in accelerated kamacite growth rates. The kamacite precipitates grow by a 3-step process: 1) diffusion of Ni along kamacite/taenite interfaces; 2) grain boundary diffusion of Ni along taenite/taenite boundaries; and 3) volume diffusion of Ni through the taenite lattice away from taenite/taenite boundaries (Fig. 6).

Ni enrichment zones develop along taenite/taenite boundaries (Figs. 3b and 4b) and taenite/kamacite interfaces (Figs. 2b and 4b), which help supply Fe to growing kamacite precipitates as Ni is removed (Fig. 6). High Ni flux along taenite/taenite boundaries results in accelerated kamacite lengthening, while high Ni flux along taenite/kamacite interfaces results in accelerated kamacite thickening. Grain boundary diffusion is particularly important in Fe-Ni system alloys because substitutional volume diffusion rates are relatively sluggish, and grain boundary diffusion makes an important contribution to the total flux of atoms. In ordinary chondrites, taenite grain boundaries most likely had a strong influence on kamacite nucleation and growth because the parent taenite particles were commonly polycrystalline.

Metallographic cooling rate programs (i.e., Wood 1964; Willis and Goldstein 1981; Hopfe and Goldstein 2001) assume that kamacite growth is limited by volume diffusion of Ni in taenite. Therefore, existing cooling rate programs probably do not accurately simulate the growth of kamacite from polycrystalline taenite in ordinary chondrites.

Crystallography of Kamacite Grain Boundary Precipitate/ Taenite Matrix Interfaces

Interfaces between a kamacite grain boundary precipitate and the surrounding taenite matrix typically have non-crystallographic (non-planar) appearances. In many cases, the irregular kamacite/taenite interfaces simply reflect the shapes of the original taenite/taenite boundaries upon which kamacite nucleation occurred.

The irregular interface shapes do not necessarily mean that kamacite and taenite are randomly oriented with respect to each other. For example, Aaronson (1962) pointed out that “...the non-crystallographic appearance which [grain boundary precipitates] usually exhibit does not reflect the crystallographic character of their lattice orientation relationships with respect to their matrix grains.” Experimental studies of the Fe-C system, where the austenite (fcc) → austenite + ferrite (bce) transformation occurs, have provided insight into the crystallographic nature of grain boundary precipitate/matrix interfaces (Honeycombe and Bhadeshia 1995). Interfaces between ferrite grain boundary precipitates and austenite matrix typically have non-crystallographic appearances, yet such interfaces exhibit high degrees of lattice coherency (Honeycombe and Bhadeshia 1995).
By analogy to the work of Honeycombe and Bhadeshia (1995), a likely mechanism of kamacite grain boundary precipitate growth is illustrated in Fig. 7. The kamacite precipitate nucleates with a Widmanstätten-type (coherent) crystallographic relationship, with respect to a taenite grain, and consumes an adjacent taenite grain that is randomly oriented. The random (incoherent) kamacite/taenite interface migrates freely due to fast Fe-Ni diffusion along the heavily dislocated interface; the kamacite/taenite interface becomes curved as it propagates into the taenite grain. The Widmanstätten-type taenite/kamacite interface, on the other hand, remains relatively flat and stationary as the precipitate grows.

Directly characterizing the crystallographic relationship between a kamacite grain boundary precipitate and the surrounding taenite matrix in the laboratory alloys is not possible because the taenite transformed to martensite upon quenching in liquid nitrogen. However, the interfaces between kamacite grain boundary precipitates and taenite matrix can be studied in slow cooled ordinary chondrite metal. In ordinary chondrites, taenite contains ~50 wt% Ni at taenite/kamacite interfaces, and such Ni-rich taenite does not transform to martensite. Preliminary electron backscatter diffraction studies of irregularly shaped kamacite grain boundary precipitate/taenite matrix interfaces in Guarena (H6) have shown that many such interfaces have a Widmanstätten-type orientation. These studies support the general kamacite growth mechanism illustrated in Fig. 7.

**Taenite and Kamacite Ni Concentrations**

If kamacite nucleates from taenite during cooling, local equilibrium should be maintained at kamacite/taenite interfaces throughout the cooling process. The Fe-Ni phase diagram shows that the equilibrium taenite Ni concentration of an Fe-9Ni alloy increases from 9 wt% at the equilibrium kamacite precipitation temperature of 700°C to >20 wt% at a final furnace temperature of 550°C (Fig. 1). Taenite Ni gradients should develop during cooling because diffusion rates decrease exponentially as temperature decreases; taenite Ni concentrations should be highest at taenite/kamacite interfaces (~20 wt%) and should decrease toward taenite cores (9 wt%). In alloys A1–A4, the regions of taenite Ni zoning close to kamacite/taenite interfaces are much too small to resolve using an electron microprobe that has a spatial resolution of ~1 µm. However, Ni enrichments of 1–2 wt% are observed at taenite/kamacite interfaces (Figs. 2b and 4b), confirming the presence of elevated taenite Ni concentrations. Interestingly, similar taenite Ni enrichments are measured at taenite/taenite boundaries (Figs. 3b and 4b). This observation suggests that fast Fe-Ni diffusion along taenite/taenite boundaries allows taenite to maintain chemical equilibrium with kamacite, even though taenite and kamacite may not be locally contiguous with one another.

In alloy A1, taenite Ni enrichments are measured at flat taenite/kamacite interfaces, where kamacite nucleation presumably occurred, but not at curved taenite/kamacite interfaces that represent advancing kamacite growth fronts. Aaronson and Domain (1966) cooled Fe-Ni-C system austenite (fcc) into the austenite + ferrite (bcc) field and observed analogous Ni enrichments in austenite at flat austenite/ferrite interfaces. Aaronson and Domain (1966) suggested that austenite Ni enrichments formed at the flat austenite/ferrite interface have a coherent (Widmanstätten-type) structure and remain stationary during cooling. The curved kamacite/taenite interface is incoherent (random) and migrates into the taenite grain during cooling. C and I represent coherent and incoherent interfaces, respectively.

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**Fig. 7. Schematic illustrating the growth of a kamacite grain boundary precipitate (K) from polycrystalline taenite (T). The kamacite precipitate nucleates along the taenite/taenite boundary, and grows into one of the parent taenite grains. The flat kamacite/taenite interface has a coherent (Widmanstätten-type) structure and remains stationary during cooling. The curved kamacite/taenite interface is incoherent (random) and migrates into the taenite grain during cooling. C and I represent coherent and incoherent interfaces, respectively.**
interfaces because the stationary nature of these interfaces allowed Ni concentrations to build up in austenite. In contrast, curved austenite/ferrite interfaces migrated continuously during cooling, precluding substantial Ni build-up in austenite. In alloys A1–A4, taenite-kamacite equilibrium most likely was maintained at all taenite/kamacite interfaces during cooling. The equilibrium taenite Ni concentration, however, was able to build up over regions large enough to detect with an electron microprobe only at the flat interfaces that remained stationary during cooling. Widge and Goldstein (1977) observed similar taenite Ni enrichments at taenite/kamacite interfaces when they cooled Fe-Ni-Co taenite into the 2-phase taenite + kamacite region.

The measured kamacite Ni concentrations of 4.6–4.8 wt% in alloys A1–A4 suggest that most kamacite growth occurred at approximately 670°C, 30° below the taenite/(taenite + kamacite) phase boundary for an Fe-9Ni alloy. The driving force for kamacite precipitation increases as temperature decreases, and undercooling is required to overcome energy barriers (i.e., the creation of a new kamacite/taenite interface) that oppose kamacite precipitation. On the other hand, diffusion rates decrease exponentially as temperature decreases. Kamacite precipitation is expected to be maximized at ~670°C because the kamacite precipitation driving force and taenite grain boundary diffusion rates are simultaneously maximized at this temperature (Reisener 2003).

Stability of Taenite Interiors

The driving force for kamacite precipitation increases as taenite undercools below the taenite/(taenite + kamacite) boundary temperature. The P-free alloys A1–A4 cooled 150–200°C below the equilibrium kamacite precipitation temperature (700°C) without forming intragranular kamacite precipitates. Apparently, the driving force is too small to overcome energy barriers associated with creating new kamacite/taenite interfaces. Taenite interiors, therefore, remain metastable and homogeneous until they cool below the martensite start temperature (~500°C for an Fe-9Ni alloy). At the martensite start temperature, taenite transforms to martensite by a diffusionless transformation. One may conclude that a monocristalline, P-free taenite particle will transform to martensite without attaining sufficient undercooling for intragranular kamacite precipitation.

On the other hand, the presence of taenite/taenite grain boundaries decreases the need to create new kamacite/taenite interfacial area and, therefore, the activation energy barrier needed to form kamacite decreases. As a result, kamacite precipitates can form at taenite/taenite boundaries even through they cannot form at taenite interiors. Note that the formation of kamacite precipitates at taenite grain boundaries did not initiate nucleation of intragranular kamacite precipitates (Widmanstätten plates) in the P-free alloys A1–A4 or in P-free ordinary chondrite metal.

The extreme stability of taenite with respect to intragranular kamacite precipitation is a thermodynamic effect and not a kinetic one. Whether or not kamacite nucleates depends on alloy energetics including: 1) the precipitation driving force; 2) the interfacial energy and strain energy barriers that oppose nucleation; and 3) the energies of structural defects that are potential sites for heterogeneous kamacite nucleation. These variables do not depend on time. Therefore, laboratory cooling experiments are useful for understanding kamacite nucleation in meteorites in spite of the difference between meteorite and laboratory cooling rates (a factor of 10⁹). The role of time is an important one, however, when one considers the growth kinetics of kamacite and the final dimensions of kamacite precipitates.

Previous Fe-Ni Alloy Cooling Experiments

The binary Fe-Ni alloys A1 and A2 contain kamacite precipitates that formed along taenite grain boundaries during cooling (~3–4°C/day). In previous papers, binary Fe-Ni taenite was cooled into the taenite + kamacite field at 2–6°C/day, and no kamacite was observed (Allen and Earley 1950; Wood 1964; Narayan and Goldstein 1984a).

These conflicting experimental results may be related to the differences in the sizes of the parent taenite grains. The Allen and Earley (1950) and Narayan and Goldstein (1984a) experiments used homogenization temperatures between 1100 and 1300°C, yielding parent taenite grains that were hundreds of microns across (Narayan and Goldstein 1984a). In the present research, alloys A1–A4 were homogenized at temperatures between 900 and 1100°C, producing taenite grains that were 50 μm across or smaller. The relatively high taenite grain boundary density in alloys A1–A4 provided abundant sites where kamacite precipitates could nucleate. In addition, many grain boundaries were available for optical observation. Also, possibly, kamacite grain boundary precipitates formed in earlier experimental studies but were overlooked as these investigators focused on searching for intragranular kamacite precipitates.

Experimental studies of phase transformations in an Fe-9 wt% Ni alloy have also been performed by Chong et al. (1998). The composition of their alloy was almost identical to the Fe-Ni alloy used in this study. They studied the taenite → taenite + kamacite transformation using cooling rates from 0.13°C/s (furnace cooling) to 420°C/s (ice brine quenching). The slowest cooling experiments of Chong et al. (1998) are about 3 × 10⁴ faster than the cooling rate used in the present study.

In the study by Chong et al. (1998), kamacite formed in the temperature range of 550–575°C during furnace cooling, and lath martensite formed in the temperature range of 380–420°C during ice brine quenching. When kamacite formed, Ni enrichment at taenite/taenite grain boundaries was observed using analytical electron microscopy with an X-ray resolution approaching 5 nm. The kamacite composition was,
However, identical to that of the matrix taenite. The authors suggested that the precipitate grew by the process of para-equilibrium rather than by maintaining equilibrium at the kamacite/taenite interface. The proposed model for kamacite growth (Chong et al. 1998) was the same as that shown in Fig. 7, where a kamacite precipitate nucleates along the taenite/taenite boundary and grows into one of the parent taenite grains.

**Phase Transformation in P-Bearing Alloys**

Doan and Goldstein (1969), Goldstein and Doan (1972), and Narayan and Goldstein (1984a, b) have cooled a number of Fe-Ni-P alloys containing taenite with >0.1 wt% P. Reisener (2003) cooled an Fe-9Ni-0.5Co-0.5P alloy (A5) in a similar manner to alloys A1–A4. The results of the earlier Fe-Ni-P alloy cooling experiments and of the alloy A5 cooling experiment are very similar, namely: 1) phosphide formed along taenite grain boundaries; 2) phosphide needles formed inside taenite grains; 3) kamacite precipitates formed at taenite grain boundaries; and 4) Widmanstätten-type kamacite needles formed inside taenite grains, probably nucleated in the presence of intragranular phosphides. Taenite grain boundaries are not necessary to produce kamacite nucleation and growth. The results of the Fe-Ni-P alloy cooling experiments confirm that chondritic metal (P-poor) and iron meteorite/pallasite metal (P-saturated) are controlled by different chemical systems, and different types of taenite transformations are to be expected during cooling.

The implications of the experimental results for understanding ordinary chondrite metal microstructures are discussed in a companion paper (Reisener and Goldstein 2003).

**CONCLUSIONS**

Likely, grain boundary kamacite nucleation and grain boundary diffusion are the applicable mechanisms for the development of much of the metal microstructures in ordinary chondrites. Existing cooling rate programs may not accurately simulate the growth of kamacite in chondritic polycrystalline taenite.

The absence of intragranular (Widmanstätten) kamacite in P-free Fe-Ni alloys indicates that monocrystalline taenite particles will transform to martensite upon cooling. The stability of P-free taenite with respect to intragranular kamacite precipitation is a thermodynamic effect and does not depend on time. Therefore, laboratory cooling experiments are useful for understanding kamacite nucleation in meteorites in spite of the difference between meteorite and laboratory cooling rates (a factor of 10^9).

Likely, monocrystalline parent taenite particles in ordinary chondrites transformed to martensite upon cooling. This transformation process could explain the metallography of zoneless plessite particles observed in H and L chondrites.

In P-bearing Fe-Ni alloys and iron meteorites, kamacite can nucleate at taenite grain boundaries and, intragranularly, as a Widmanstätten pattern. Therefore, ordinary chondrite metal (P-free) and iron meteorite/pallasite metal (P-bearing) are controlled by different chemical systems and different types of taenite transformation processes.

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**Editorial Handling**—Dr. Edward Scott

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