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Two types of metal particle in the Bachmut (L6) chondritic meteorite

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ABSTRACT. Metal particles in the Bachmut chondrite may be subdivided into *large* (hundreds of μm in size) and *small* (1–10 μm in size) varieties. They differ in the ratio of their constituent phases, in structure, and in chemical composition. *Large* particles are richer in Ni than *small* ones, the latter being characterized by an abnormally high Cu content. It is suggested that different pre-accretion histories were responsible for producing the various types of metal grains, and that, during post-accretion thermal history, temperatures were too low to cause elemental redistribution among the grains.

KEYWORDS: meteorite, chondrite, Bachmut, metal particles.

THE Bachmut meteorite comprises 88.2 vol. % silicates (olivine, orthopyroxene, and devitrified glass), 2.6 % plagioclase, 4.5 % Fe, Ni metal, 4.3 % troilite, and 0.4 % chromite. The following phases have been identified as discrete grains: clinopyroxene, maskelynite, ilmenite, native copper (Semenenko *et al.*, 1979); chalcopyrrhotine (Ramdohr, 1973): merrillite (Zavaritsky and Kvasha, 1952); in the fusion crust, magnesioferrite (Semenenko and Melnikov, 1980). Shock metamorphic features exhibited by the meteorite are, fissuring and undulatory or mosaic extinction of olivine grains; fracturing in chromite and, more rarely, in troilite and pyroxene grains; plagioclase displaying undulatory extinction, with some grains converted to maskelynite. Sporadic melting has occurred in troilite, Fe, Ni, and silicate. Comparison of these features with experimental data indicates that the shock pressure to which the meteorite was probably subjected in space was approximately 200–250 kbar (Semenenko, 1977).

Nickel-iron occurs as kamacite (3.1 vol. %), taenite (1.0 %) and plessite (0.4 %), and the metal particles may be subdivided into two different types distinguishable by their size. *Large* metal particles, ranging from tens to hundreds of micrometres, are present in the interchondrule matrix of the meteorite. In contrast, *small* metal particles, ranging up to a few tens of micrometres, occur essentially around chondrules, but are rarely present within chondrules or among the silicate minerals of the matrix. In this last instance the matrix may be composed of fragmented chondrules. In some areas of matrix 'small' metal particles are situated among 'large' ones, but the former tend to occur closer to chondrule margins. In addition to size, 'large' particles may be distinguished from 'small' particles on the basis of phase relationships, structures, and compositions of the phases.

'Large' metal particles. In polished sections kamacite is seen to predominate, and occurs either on its own or as intergrowths with taenite. 'Large' particles contain kamacite with a constant Ni content close to 6.0 wt. %, but the mineral may also contain small amounts of Cu, S, and P (Table I, analysis 1).

Both clear and zoned taenite are present. Clear taenite occurs as intergrowths with kamacite, some tens of micrometres wide and of constant composition, the Ni content of under 30 % being unusually low (Table I, analysis 2) compared with clear taenite in other chondrites (Taylor and Heymann, 1971). The absence of zoning in Bachmut clear taenite is because it has a Ni content below the range (30–40 %) in which plessite of type IV may form. Plessite of type IV, originally known as 'dark etching taenite', forms by the precipitation of randomly oriented kamacite within taenite.

The composition of such kamacite–taenite pairs in Bachmut (Table I, analyses 1 and 2, and 3 and 4) is similar to that in the analogous metal particles in Holbrook (L6) that has also undergone shock reheating (Sears and Axon, 1976).

Zoned taenite comprises two, three or four zones (Semenenko *et al.*, 1979), there being a direct relationship between the number of zones and grain-size. This in turn suggests that the number of zones observed depends on the position of the plane of the section relative to the centre of each metal grain; the apparent centre of a grain may not coincide with the real one (Semenenko, 1975). Two types of metallic particle with four zones may be

TABLE I. Microprobe data of the metal particles in the Bachmut[1] meteorite (wt.%)

Element	Large particles								Small particles						
	Intergrowth of kamacite[1] with unzoned taenite[2]		Intergrowth of kamacite[3] with unzoned taenite[4]		Grain I of zoned taenite		Grain II of zoned taenite		Particles of microstriped plessite				A zoned particle of taenite (fig.7)		
	1	2	3	4	5	6	7	8	9[3]	10	11	12[4]	13	14	15
Fe	93.3	72.3	91.7	66.9	72.0	65.8	72.3	64.2	79.3	75.9	77.3	77.1	n.d.	77.2	71.0
Ni	5.9	27.6	6.0	31.3	28.2	34.1	28.0	35.9	18.1	22.2	20.2	20.4	31.4	17.4	26.1
Co	1.0	0.5	1.2	0.7	0.3	0.4	0.4	0.4	0.8	0.7	0.7	0.6	n.d.	1.4	1.1
Cu	0.1	0.0	0.0	0.0	tr.	0.0	0.4	0.4	0.9	1.0	1.3	1.4	1.3	2.9	1.1
P	tr.	tr.	0.0	0.0	tr.	0.0	0.0	0.0	0.0	0.0	0.1	0.1	n.d.	0.0	0.0
Si	0.0	tr.	0.0	0.1	tr.	0.1	0.1	tr.	0.0	tr.	tr.	0.0	n.d.	0.0	0.0
Cr	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	tr.	tr.	n.d.	0.0	0.1
S	tr.	0.0	0.0	0.0	tr.	0.0	tr.	tr.	tr.	tr.	0.1	tr.	n.d.	tr.	tr.
Total	100.3	100.4	98.9	99.0	100.5	100.5	101.3	101.0	99.1	99.8	99.7	99.6	–	98.9	99.4

[1] Composition of elements was determined on a MAR-1 microanalyser. Analytical conditions: for Si, P the accelerating voltage was 10kV; for the other elements, 20kV; the probe current was 1×10^{-6}A; the diameter of the beam was 3μm. Metals of high purity (99.99%) were used as standards, and SiO_2 and GaP for Si and P respectively. Precision of measurement is 1.5% relative.

[2] Points 5, 7 are the cores of acicular plessite in the particles of zoned taenite and points 6, 8 are a zone of taenite type II in the same particles.

[3] Fig.3

[4] Fig.4

n.d. = not detected

tr. = trace

distinguished by the structure of the plessite forming the core, which may be either acicular or micrographic. In each type the order of zones is, from the rim inwards: taenite 1, plessite IV, taenite II and coarse plessite.

In the first type the plessite of the core is acicular and similar to martensite, the taenite needles being 10 x 0.7–0.2 x 0.2 μm, and the other phase, assumed to be kamacite, ranging from 5 x 0.4–0.1 x 0.1 μm in size. The resolution of our electron probe, with a beam diameter of 3 μm, was insufficient for the analysis of individual phases in plessite. The relative volume of taenite to kamacite in acicular plessite is 1.6. The nickel distribution in these metal particles has an M-shaped profile from 25 % (wt.) in the centres to 45 % at the margins (Semenenko *et al.*, 1979). Metal particles with acicular plessite cores contain small amounts of Cr and Si, and, in one, 0.4 % Cu (Table I, analyses 5 and 6; and 7 and 8).

In the other type of large metal particle the plessite core has a micrographic structure. Plessite with this structure is common in the meteorite. It forms not only the cores of zoned metal particles but also occurs in some disordered regions in taenite grains (fig. 1*a*) and as some discrete particles of plessite (fig. 1b). In each case, the particle always has a rim of taenite. The taenite to kamacite ratio in micrographic plessite is 1.3 to 1.4. The Ni content in taenite ranges up to 50 % (wt.), while in kamacite it is about 6 % (Semenenko *et al.*, 1979), the same as in discrete kamacite grains. The average Ni content of micrographic plessite, 31.5 %, calculated from the proportions of the phases by volume, is higher than that of acicular plessite.

'Small' metal particles. In 1975 it was noted that in some chondrites small metal particles are present that differ greatly in structure from large metal grains within the meteorite (Sears and Axon, 1975; Semenenko, 1975). The structure of small metal particles was subdivided into three types: micrograpic, microstriped, and microspotted (Semenko, 1975). Sears and Axon (1975) called these particles 'zoneless plessite'. Some microstriped particles have three parallel systems of stripes and their appearance has been referred to as a 'pseudo-Widmanstätten texture' (Hutchison and Bevan, 1983). Microspotted plessite is also called plessite with blocky structure. Further examination of the composition of the small metal particles showed that these are not only plessitic but may also be of zoned taenite (Semenenko *et al.*, 1984*a*, *b*). Their characteristic composition has lower Ni than that of large metal grains (Sears and Axon, 1975; Gooding *et al.*, 1979; Hutchison *et al.*, 1981; Semenenko *et al.*, 1984*a*, *b*).

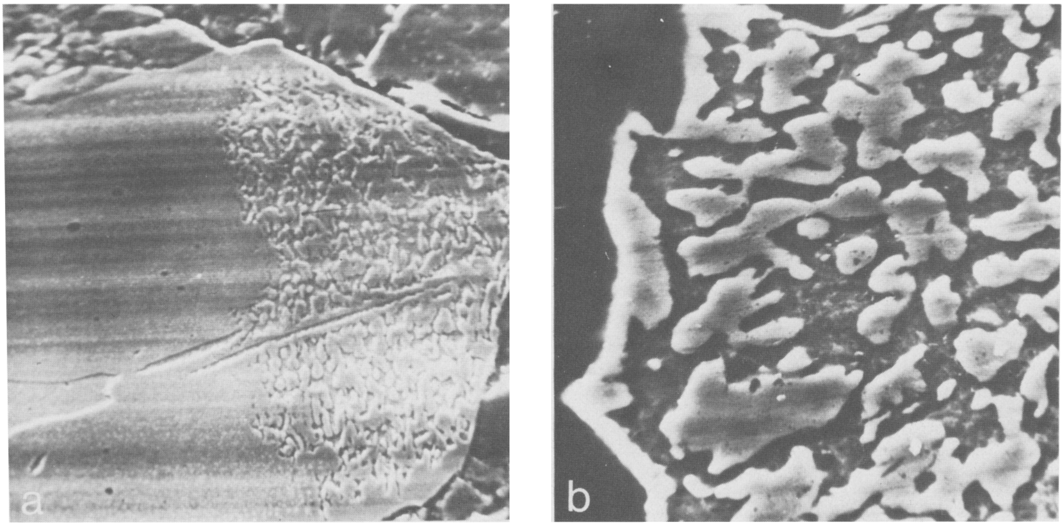

FIG. 1. Electron micrographs. (*a*) Large metal grain (× 3100), comprising taenite and plessite with micrographic texture that probably formed by a discontinuous precipitation reaction (Grokhovsky and Bevan, 1983). (*b*) Large metal grain (× 2300) completely composed of micrographic plessite and situated on the surface of a chondrule. Taenite is white, kamacite, dark grey. Note the rim of taenite.

Shock metamorphism in space has rendered Bachmut (and Zaborzika) structurally different from unreheated chondrites (Hutchison *et al.*, 1981; Hutchison and Bevan, 1983), but common to all is the occurrence of unzoned plessite and small zoned taenite particles. 'Small' metal particles in Bachmut are mainly plessitic, or, occasionally, of zoned taenite comprising two or three zones; some particles have a complex structure. Three types of plessitic structure are recognized in the small metal particles (Semenenko, 1975).

The most common type is microstriped plessite, characterized by subparallel orientation of the taenite spindles (fig. 2*a*), a taenite rim to the particle usually being absent. The interphase boundaries are sharp, and taenite 'stripes' have slightly wavy boundaries, and are sometimes undulating. Taenite stripes are generally 11 × 0.2–1.0 × 0.1 μm in size. The ratio of taenite to kamacite varies from 1.4 to 4.4 in different particles. In some cases two intersecting systems of stripes are observed. Small particles have plessite with a nickel content (18–22 %) lower than that in large particles (Table I, analyses 9–12). Specific to the small particles of microstriped plessite is a high Cu content, 0.9–1.4 % (wt.). Only once was a taenite rim observed on a particle of microstriped plessite (fig. 2*b*), and the plessite was found to have the same composition as in other rimless, particles (Table I, analysis 12).

Rare plessite particles with a microspotted structure (fig. 3*a*) are characterized by an irregular arrangement of lobate intergrowths of kamacite and taenite. Taenite crystallites range from 18 × 10–1 × 1 μm in size, and the ratio of taenite to kamacite is only 0.3–0.4, and lower than in other types of plessite.

Small round metal particles consist of microstriped plessite (fig. 3*b*) and taenite with two or three (fig. 3*c*) zones. Those with three zones have an unusual structure different from that of taenite in large metal particles. Each particle consists of a taenite rim, a zone that we suppose to be of taenite with lower Ni content, and a core of microstriped plessite. Alternatively (fig. 3*c*) the taenite particle consists of a taenite rim 5 μm wide, a zone of micrographic plessite 2–27 μm wide and a core of taenite. The one described and analysed has an unusually high Cu content (< 2.9 %, Table I, analyses 13–15), and a lower Ni content than large particles of taenite with three zones. The micrographic texture of the second (plessitic) zone of this particle should be emphasized for it is this that structurally distinguishes the particle from large metal particles, which contain plessite of type IV. The extraordinary structure of the small particle is associated with a lower Ni abundance in each of its zones compared with the large, zoned particles. Our electron probe with a diameter of 3 μm was unable to resolve kamacite and taenite in the micrographic plessite. The bulk analysis obtained

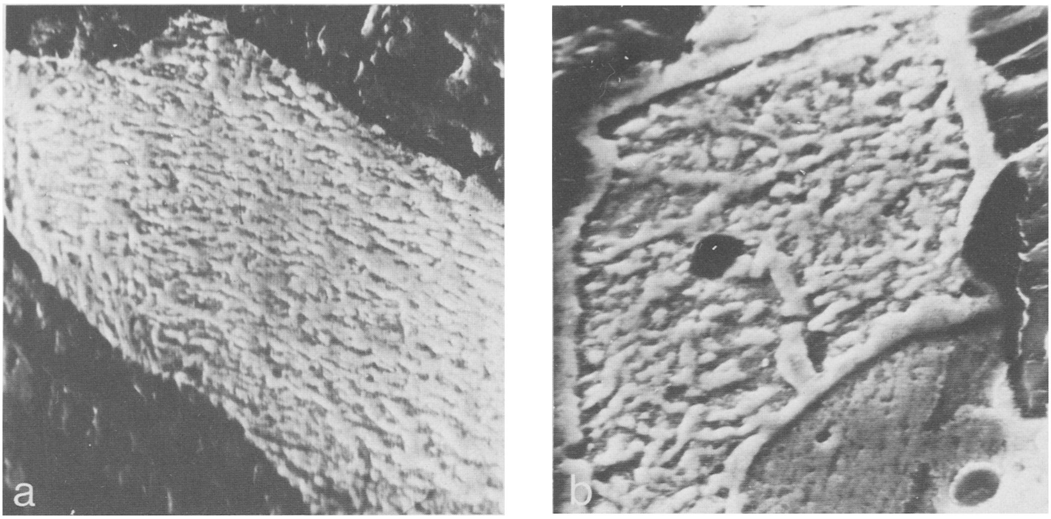

FIG. 2. Electron micrographs. (*a*) Small metal particle of microstriped plessite (× 480) in matrix within larger particles of kamacite and troilite (*c*.20 μm). Note the absence of a rim of taenite. (*b*) Small particle of microstriped plessite (× 1600) on the surface of a chondrule. Note the rim of taenite, rarely present on such grains. The ratio of taenite to kamacite is 1.4.

showed that this plessite (Table I, analysis 14) has a lower Ni content than the taenite core (Table I, analysis 15). It is important to note the abnormally high content of Cu (1.1–2.9 wt. %) in zoned particles and the lack of correlation between Cu and Ni abundances, which are reflected in the extreme value for Cu in the zone of micrographic plessite (2.9 % Cu and 17.4 % Ni). The Cu content of the plessite is almost three times higher than that of the rim, which is richest in Ni.

Discussion. The two types ('large' and 'small') of metal particle differ in their phase relations, structure and composition.

1. In the large particles kamacite is predominant, whereas taenite predominates in the small ones.

2. The particles differ in the structure of their plessite and zoned taenite. Large particles have two types of coarse plessite, acicular plessite possibly derived from martensite, and micrographic plessite, which differ in Ni content. In the small particles plessite may be microstriped, microspotted, micrographic, or more complex in structure. In all

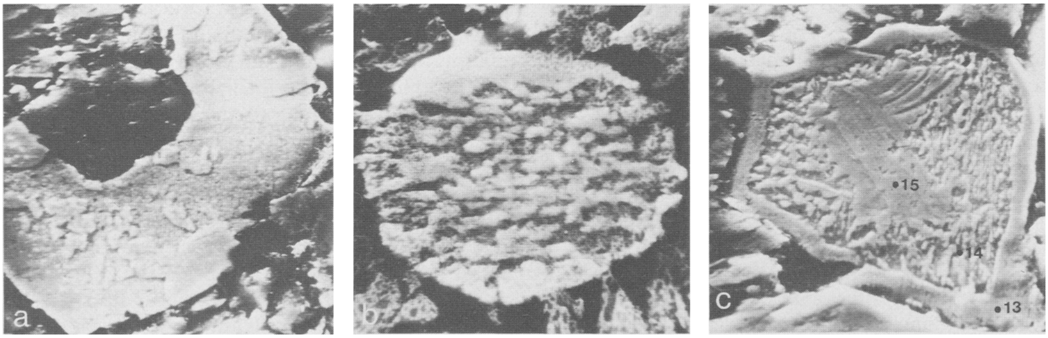

FIG. 3. Electron micrographs. (*a*) Small metal grain of microspotted plessite (× 750). (*b*) Small metal grain within a chondrule (× 2300). The grain is essentially taenite in two zones. (*c*) Small metal particle on a chondrule surface (× 520). The taenite particle comprises three zones: a core of taenite surrounded by micrographic plessite with a taenite rim. Analyses of points 13, 14, and 15 are given in Table I.

cases the nickel content (18–22 %) is lower than in plessites in large particles. It is this difference in nickel content that is the cause of the different structure of zoned taenite between large and small particles.

The absence of plessite IV requires special discussion. According to data in the literature (Scott, 1973); Lin *et al.*, 1979) this type of plessite may only form within metal with a bulk Ni content in the range 30–40 %. From our work we have shown that small metal particles in Bachmut typically have Ni contents (17.3–31,4 %) below this range.

3. The plessite and zoned taenite in large particles have different Ni contents from those in small particles. In the former the range is 28–50 % Ni, whereas in small particles it is 17.4–31.4 %. It is generally accepted that the Ni content in taenite varies inversely with grain-size (Wood, 1967; Fisenko *et al.*, 1981). However, this really applies only to large taenite particles of which the Ni content and apparent size are often determined by the position of the plane of the section relative to the centre of each grain. The various sections of large particles are in fact correlated. In small sections of large grains, but not in small grains, the Ni content is, as a rule, higher than in large ones.

4. Small metal particles have an unusually high Cu content (0.9–2.9 %). It must be pointed out that native copper occurs in micrographic plessite of large particles, and abnormally high Cu abundances occur in micrographic plessite of small particles. There is no positive correlation between Cu and Ni in small particles (Table I), which contrasts with the data obtained for iron meteorites and for some chondrites (Clarke and Jarosewich, 1978).

Differences in the composition of the phases between large and small particles in Bachmut may have resulted from compositional differences among the particles before agglomeration. Either the particles are samples of different source materials, or they are samples of material from a single source but with diverse thermal histories. We argue that the second alternative is the more probable. Small particles could represent primary metal, some of which was reprocessed to produce the precursor material of the large particles. One suggestion (Fisenko *et al.*, 1981) is that a proportion of small grains suffered recondensation followed by slow cooling and enlargement with the appearance of kamacite which resulted in an increased Ni content in the taenite phase. This could have led to the observed predominance of the kamacite phase in large particles, together with higher Ni contents in taenite and plessite, in comparison with small particles. We thus conclude that the two types of metal particles are original constituents of the parent body. After agglomeration, although they shared the same thermal history, the differences in primary composition resulted in the variety of composition and structure in plessite and zoned taenite.

In Bachmut, Zaborzika, Kharkov, and Zvonkov, small metal particles occur around, but not within, relic chondrules, which has been observed in other chondrites by many workers. This observation may be interpreted as the adherence of metal particles, a component of the dust in a solar nebula, on to the plastic surfaces of chondrules. Chondrules of Elenovka, Saratov, and Alexandrovsky have been studied by electron microscopy, and the presence of dust particles adhering to the surfaces was found to be a characteristic of the morphology of the chondrule surfaces (Semenenko and Sobotovich, 1983).

The suggestion that large and small metal particles had different thermal histories before accretion is supported by the distribution of Cu. The highest concentrations of Cu are associated with micrographic plessite. In the large particles we observe native copper, but in small particles the Cu is dispersed. From the experimental data of Houdremont (1960) the highest concentration of Cu (8 %) occurs in γ-Fe at 1094 °C. The solubility of Cu is lower in α-Fe, the maximum being 1.4 % at 850 °C. At lower temperatures the solubility decreases and excess Cu is precipitated. The difference in the solubility of copper causes native copper to be precipitated during the $\gamma \rightarrow \alpha$ transformation on cooling. This is suggested as the mechanism for the appearance of native copper in the micrographic plessite of large metal particles.

Abnormally high concentrations of dispersed Cu in small particles (0.9–2.9 %) are a new observation. Earlier investigations (Clarke and Jarosewich, 1978) found the Cu content in small taenite particles to have a maximum of 0.29 %, and to be positively correlated with Ni abundance. The difference in Cu content between large and small metal particles provides evidence for their different cooling rates before accretion. Small particles cooled faster than large ones. From the Fe–Cu phase diagram (Houdremont, 1960), metal with 2.9 % Cu must have cooled rapidly from 875 °C, suggesting that Bachmut accreted at a lower temperature. After accretion the material could not have been reheated to a higher temperature.

Thus, the best explanation of the differences in size, phase relations, structure and composition of nickel–iron particles is that they had different pre-accretion thermal histories. Some proportion of the small particles represents the precursor material of the large ones. This is in agreement with the conclusion of Sobotovich (1974) who first established, using lead isotopic data, that meteoritic material was heterogeneous during accretion. It has been shown that small metal particles are present in chondrites not only of various chemical groups and petrologic types (Sears and Axon, 1975; Gooding *et al.*, 1979; Hutchison and Bevan, 1983; Semenenko *et al.*, 1984*a*), but also in chondrites with different thermal histories. Initially, small, zoneless plessite particles were found in unreheated chondrites, but now such particles are known to occur in Bachmut and Zaborzika (Semenenko *et al.*, 1984*a*) that were reheated. The fact that small metal particles are widely distributed among chondrites is supporting evidence for the occurrence of two types of metal particle in the precursor material of chondrites, and cannot be accounted for by post-accretion processes. The survival of the two types of metal bears witness that chondrites accreted at a temperature at which diffusion of Fe and Ni between the different particles was severely limited. The temperatures attained after accretion could not have risen high enough to produce elemental redistribution among the metal particles. For example, in Bachmut, a proportion of small metal particles have a zoned structure and composition that are indicative of reheating to a peak temperature not greater than 350 °C.

Our results touch not only upon the origin of zoning in the metal particles, their accretion temperature, their post-accretion thermal history and the cooling rates of chondrite parent bodies, but also on the question of the origin of the various petrologic types of chondrites.

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