Fe, Ni, Co, and Cu in FeNi alloys of H Chondrites

K Blutstein1,* and S Pawliszyn1

1Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology; Wybrzeże S. Wyspiańskiego 27; 50-370 WROCŁAW

*Corresponding author: konrad.blutstein@pwr.edu.pl

Abstract. This publication presents the results of chemical analyses of 173 FeNi alloy grains from four selected H ordinary chondrites: Thuathe, Chergach, Gao-Guenie and NWA 4555. Based on performed analyses and calculations, the following average chemical composition of the FeNi alloy was determined [in wt.%]: Fe – 90.75%; Ni – 8.80%; Co – 0.35%; Cu – 0.03%. The content of Cu and Co depends on the nickel content in the FeNi alloy. The low-nickel alloy represented by kamacite is enriched in cobalt (average content 0.38%) and depleted in copper (0.01%), while the high-nickel alloy, represented mainly by taenite, is characterized by a low content of cobalt (0.08%), and a significant enrichment in copper (0.16%). Based on these data, it is possible to approximate the resources of these metals in the parent bodies of these chondrites. For example, for the asteroid (143624) 2003 HM16, which is classified as a Near Earth Object (NEO), such resources are [in Mg]: Fe – 2.4 · 10⁹, Ni – 2.3 · 10⁸, Co – 9.2 · 10⁶, Cu – 7.9 · 10⁵.

1. Introduction

Widely understood extraterrestrial mining is a subject of research in many scientific centres around the world, including Université Grenoble Alpes [1], Hungarian Academy of Science, ESA [2,3], Mount Holyoke College (USA) and The Open University (UK) [4]. Luxembourg initiative, which brings together scientists from various universities and institutions, makes specific plan for space mining [5]. At the Wrocław University of Science and Technology, the first research on extraterrestrial matter began at the end of the 20th century and continues to this day [6-12]. This is due to the awareness of the limitations that prevail on our planet. On the one hand, there are limitations related to the possibility of obtaining raw materials on our planet, and on the other, more importantly, economic limitations related to the transport of raw materials outside our planet. It is the latter factor that is the main reason behind the development of extraterrestrial mining. Building bases or colonies outside the Earth requires a lot of resources. The raw materials themselves are relatively cheap compared to the cost of transport, which exceed the budget of many countries. Among the raw materials necessary for human presence outside the Earth, there will certainly be energy resources, as well as metallic ones and water [13]. This situation forces us to obtain raw materials at the place of their need or nearby. One of such objects are asteroids.

Of the asteroids, the parent bodies of chondrites are the best recognized for their chemical and mineral composition. This is because they are mainly undifferentiated bodies, and therefore their composition is homogeneous [7]. With a relatively small number of samples that reach the Earth each year in the form of meteorites - chondrites, the resources for entire asteroids can be estimated with fairly high accuracy. The most abundant meteorites on Earth are the ordinary chondrites, and the most
The asteroids of the S (IV) type are considered to be the parent bodies of ordinary chondrites \([14-16]\). It is commonly believed that the parent body of the H group ordinary chondrites is the asteroid 6 Hebe \([17]\), and additionally on the basis of spectroscopic examinations it is possible to select other potential parent asteroids, of those orbiting much closer to the Earth, the so-called NEO (Near Earth Objects): (16960) 1998 QS52, (99901) 1989 VA, (138524) 2000 OJ8, (143624) 2003 HM16, (159857) 2004 LJ \([18]\) and other asteroids in the main belt, e.g.: (214869) 2007 PA8 \([19]\), 148 Galia, 101 Helena, 67 Asia, 57 Mnemosyne, 32 Pomona, 23 Thalia, 14 Irene, 5 Astræa \([20]\).

The FeNi alloy grains are a component of chondrites of interest to potential extraterrestrial mining. These grains can be a source of not only iron and nickel, but also copper and cobalt. FeNi alloy is made of three mineral phases - kamacite, taenite and tetrataenite. Kamacite has an iron content of 92.5–96.0 wt.\% and nickel 4.0–7.5 wt.\% \([21]\), taenite contains 55–75% iron and 25–45% nickel and tetrataenite contains 44–52% iron and 48–56% nickel \([22]\). In the group H of ordinary chondrites about 90% of the FeNi alloy is kamacite, and the remaining 10% is taenite \([23]\). The H chondrite kamacite contains 0.34–0.78 wt.\% Co and <0.06 wt.\% Cu. The H chondrite taenite contains 0.11–0.55 wt.\% Co and 0.13–0.40 wt.\% Cu, while the tetrataenite contain 0.11–0.18 wt.\% Co and 0.33–0.38 wt.\%. Cu \([24]\). Clarke and Scott \([22]\) report similar ranges of Co and Cu occurrence in tetrataenite (<0.2–2.0 wt.\% Co and 0.11–0.36 wt.\% Cu). The kamacite of the equilibrated H chondrites contains on average 0.47 wt.\% Co (0.44–0.51 wt.\%) \([25]\). Additionally, the petrographic type of the meteorite is also important for copper \([12,26]\).

The aim of the research presented in this article was to determine and characterize the chemical composition of the FeNi alloy and the mineral phases that form it, occurring in the parent bodies of the H group common chondrites.

2. Materials and Methods

Four H-group meteorites were analysed: Thuathe (H4/5), Gao-Guenie (H5), Chergach (H5) and NWA 4555 (H4) purchased by the Wrocław University of Science and Technology. The test samples were prepared in the form of thin sections with a thickness of 0.03 mm. The samples were coated with graphite. The samples prepared in this way could be tested with the use of SEM (scanning electron microscope).

The analyses of the elemental composition of the FeNi alloy were conducted on the CAMECA SX-FIVE FE electron microprobe at the Laboratory of Earth Sciences and Mineral Engineering (GEO-SEM) of the Wrocław University of Science and Technology. The measurements were performed under the following conditions: 15 kV of accelerating voltage and 20nA of beam current. FeNi alloy grains showing no weather changes were selected for the analyses. The grains were recognized based on the colour intensity in the BSE (backscattered electrons) image and the EDS (energy-dispersive X-ray spectroscopy) spectrum. The contents of Fe, Ni, Co, and Cu were measured.

Around 50 grains were measured for each meteorite samples: the Gao-Guenie, Chergach and NWA 4555, and 30 grains were measured for the Thuathe sample. The results with a deviation of 100% +/-3% were selected for further analysis.

As a result of the analyses, the minimum and maximum values of the content of the examined elements, their mean value, median and standard deviation were obtained. The allocation of the given FeNi alloy grains to a specific mineral phase was made on the basis of the nickel content.

3. Results

Tables 1–4 show the data for the Thuathe, Chergach, Gao-Guenie and NWA 4555 meteorites, divided into individual mineral phases. The presented data on the elemental composition, especially the mean content and the median, are very similar. It is worth noting that in the NWA 4555 meteorite none of the analysed grain was recognized as a tetrataenite. Moreover, in the Thuathe meteorite, cobalt is present in a significantly increased concentration in three taenite grains.
Table 1. Thutathe chemical composition of selected FeNi alloy minerals

| Mineral   | kamacite |       | taenite |       | tetrataenite |       |
|-----------|----------|-------|---------|-------|--------------|-------|
| Element   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   |
| Min       | 94.94 | 4.40 | 0.33 | 0.00 | 56.05 | 22.88 | 0.00 | 0.06 | 51.26 | 48.58 | 0.01 | 0.25 |
| Max       | 96.54 | 6.42 | 0.43 | 0.03 | 76.26 | 42.68 | 0.90 | 0.35 | 52.73 | 50.14 | 0.10 | 0.29 |
| Mean value| 95.90 | 5.81 | 0.38 | 0.01 | 64.28 | 35.74 | 0.15 | 0.19 | 51.98 | 49.27 | 0.05 | 0.27 |
| Standard deviation | 0.56 | 0.70 | 0.03 | 0.01 | 5.66 | 5.26 | 0.25 | 0.08 | 0.74 | 0.79 | 0.05 | 0.02 |
| Median    | 96.15 | 6.06 | 0.38 | 0.00 | 63.50 | 36.58 | 0.06 | 0.19 | 51.94 | 49.10 | 0.03 | 0.27 |
| No. of analysed grains | 7 | | | | | | | | | | | 28 |

Table 2. Chergach chemical composition of selected FeNi alloy minerals

| Mineral   | kamacite |       | taenite |       | tetrataenite |       |
|-----------|----------|-------|---------|-------|--------------|-------|
| Element   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   |
| Min       | 91.68 | 4.46 | 0.34 | 0.00 | 55.14 | 25.52 | 0.00 | 0.07 | 46.57 | 48.76 | 0.00 | 0.18 |
| Max       | 96.35 | 6.57 | 0.40 | 0.06 | 72.43 | 42.79 | 0.10 | 0.32 | 49.96 | 50.81 | 0.03 | 0.28 |
| Mean value| 93.07 | 5.94 | 0.37 | 0.02 | 65.24 | 33.36 | 0.05 | 0.17 | 47.90 | 49.87 | 0.01 | 0.25 |
| Standard deviation | 1.05 | 0.41 | 0.02 | 0.02 | 5.67 | 5.54 | 0.03 | 0.06 | 1.65 | 0.90 | 0.01 | 0.05 |
| Median    | 92.88 | 6.02 | 0.38 | 0.01 | 66.49 | 32.32 | 0.05 | 0.14 | 47.54 | 49.95 | 0.01 | 0.26 |
| No. of analysed grains | 21 | | | | | | | | | | | 45 |

Table 3. Gao-Guenie chemical composition of selected FeNi alloy minerals

| Mineral   | kamacite |       | taenite |       | tetrataenite |       |
|-----------|----------|-------|---------|-------|--------------|-------|
| Element   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   | Fe  | Ni  | Co   | Cu   |
| Min       | 91.02 | 5.34 | 0.35 | 0.00 | 57.70 | 27.86 | 0.01 | 0.11 | 49.19 | 49.19 | 0.00 | 0.21 |
| Max       | 94.33 | 6.82 | 0.44 | 0.05 | 71.72 | 39.89 | 0.12 | 0.24 | 52.43 | 52.43 | 0.04 | 0.35 |
| Mean value| 92.56 | 6.11 | 0.39 | 0.01 | 64.55 | 33.71 | 0.06 | 0.16 | 50.73 | 50.73 | 0.01 | 0.27 |
| Standard deviation | 0.72 | 0.46 | 0.02 | 0.02 | 4.40 | 4.02 | 0.03 | 0.04 | 1.05 | 1.05 | 0.01 | 0.05 |
| Median    | 92.58 | 6.17 | 0.39 | 0.00 | 64.11 | 33.79 | 0.05 | 0.15 | 50.68 | 50.68 | 0.01 | 0.27 |
| No. of analysed grains | 35 | | | | | | | | | | | 51 |
Table 4. NWA 4555 chemical composition of selected FeNi alloy minerals

| Mineral | kamacite | taenite |
|---------|----------|---------|
| Element | Fe       | Ni      | Co    | Cu | Fe   | Ni | Co | Cu |
|         | wt.%     |         |       |    | wt.% |     |    |    |
| Min     | 90.89    | 5.42    | 0.32  | 0.00| 55.60| 23.50| 0.01| 0.07|
| Max     | 94.49    | 7.03    | 0.42  | 0.06| 76.09| 43.74| 0.11| 0.26|
| Mean value | 92.52 | 6.54    | 0.37  | 0.02| 69.41| 29.64| 0.06| 0.15|
| Standard deviation | 0.81 | 0.41    | 0.03  | 0.02| 5.20 | 5.20 | 0.03| 0.05|
| Median  | 92.50    | 6.66    | 0.38  | 0.01| 70.29| 28.61| 0.06| 0.14|
| No. of analysed grains | 33 | 16 | 49 |

Table 4 shows the data for the individual mineral phases calculated for the entire H group. In total, the measurements of 173 FeNi grains were considered for the analysis, including 96 kamacite grains, 64 taenite grains and 13 tetrataenite grains. The calculated values of the average content of selected metals in the given mineral phases correspond quite well with the determined median value. The greatest variability in chemical composition is characteristic of taenite, which, however, constitutes only 10% of the FeNi alloy in ordinary chondrites. Kamacite, which constitutes 90% of this alloy, shows little variability.

Table 5. H ordinary chondrite chemical composition of selected FeNi alloy minerals

| Mineral | kamacite | taenite | tetrataenite |
|---------|----------|---------|--------------|
| Element | Fe       | Ni      | Co   | Cu | Fe   | Ni | Co | Cu | Fe   | Ni | Co | Cu |
|         | wt.%     |         |       |    | wt.% |     |    |    | wt.% |     |    |    |    |
| Min     | 90.89    | 4.40    | 0.32  | 0.00| 55.14| 22.88| 0.00| 0.06| 45.88| 48.58| 0.00| 0.18|
| Max     | 96.54    | 7.03    | 0.44  | 0.06| 76.26| 43.74| 0.90| 0.35| 52.73| 52.43| 0.10| 0.35|
| Mean value | 92.90 | 6.20    | 0.38  | 0.01| 65.90| 33.16| 0.08| 0.17| 48.67| 50.13| 0.02| 0.26|
| Standard deviation | 1.18 | 0.52    | 0.02  | 0.02| 5.64 | 5.53 | 0.14| 0.06| 2.16 | 1.07 | 0.03| 0.04|
| Median  | 92.73    | 6.27    | 0.38  | 0.01| 66.37| 33.23| 0.05| 0.15| 48.13| 50.35| 0.01| 0.27|
| No. of analysed grains | 96 | 64 | 13 |

Graph 1 shows the dependence of iron content on nickel. There is a clear border delineated by empty space, between kamacite and taenite, as well as taenite and tetrataenite. It is also noticeable that there is very little variation in the content of nickel in relation to iron in kamacite. Graph 2 shows the dependence of the cobalt and copper content in relation to the Ni/Fe ratio. This graph shows very clearly that the highest concentration of cobalt is in kamacite, above 0.3%, while in taenite this content is low, below 0.15% (excluding the three anomalies with a concentration exceeding 0.4%) and decreases with increasing nickel content. The opposite situation is visible in the case of copper, where kamacite has the lowest content of this metal (max. 0.06%), and the highest concentrations are achieved in taenite and tetrataenite, where the content increases with increasing nickel content in the alloy. The separated population of points, that are vertically aligned between 0 and 0.20 Ni/Fe ratio, results from the low variability of the content of iron and nickel in kamacite.
Graph 1. Abundance of Fe and Ni in analysed FeNi alloy grains

Graph 2. Abundance of Co and Cu in relation to Ni/Fe ratio in analysed FeNi alloy grains

Table 6 shows the average composition of the FeNi alloy for individual meteorites and for the entire H group. The chemical composition of the individual meteorites is almost identical. The results differ only slightly for iron, which is most likely related to the measurement inaccuracy of this element.

| Element       | Fe    | Ni    | Co  | Cu  |
|---------------|-------|-------|-----|-----|
| Thuathe       | 92.74 | 8.81  | 0.36| 0.03|
| Chergach      | 90.29 | 8.68  | 0.34| 0.03|
| Gao-Guenie    | 89.76 | 8.87  | 0.36| 0.03|
| NWA 4555      | 90.21 | 8.85  | 0.34| 0.03|
| H chondrite ore | 90.75 | 8.80  | 0.35| 0.03|

Table 6. Chemical composition of FeNi alloy
4. Discussion
The identification of individual mineral phases was carried out based on nickel content in the alloy. Standard kamacite grains are characterized by nickel content of 4 to 7.5% [21], and taenite grains of 25-45% [22]. FeNi grains with nickel content above 48% may represent tetrataenite [22], however, the authors do not have data on the structure of these grains that could confirm the thesis. Tetrataenite is present in ordinary chondrites in a small amount and has little influence on the result. It was assumed that the average mineral composition of the FeNi alloy is 90% kamacite and 10% taenite [23].

Based on the obtained results, the chemical composition of the FeNi alloy was determined for the entire H ordinary chondrites group. This alloy contains an average of 90.75 wt.% iron, 8.90 wt.% nickel, 0.35 wt.% cobalt and 0.03 wt.% copper. Moreover, it was also observed that the highest concentration of cobalt occurs in the FeNi phase represented by kamacite: average and median 0.38%, with the range from 0.32% to 0.44%. In taenite, the average concentration is 0.08%, the median is 0.05% with a range from 0 to 0.90%, however, three of the copper taenite grains had an abnormal cobalt content. When excluded, the range is 0 to 0.14%. In the case of copper, the situation is the opposite. The lowest enrichment is characteristic of kamacite: average value and median 0.01%, with contents from 0 to 0.06%, while for taenite the average value is 0.17%, median 0.15%, and the range is from 0.06 to 0.35%.

Based on the obtained data, it is possible to try to determine the metallic resources of asteroids, which are potential parent bodies of H ordinary chondrites. An example is the Near-Earth Object (NEO) (143624) 2003 HM16 asteroid. Assuming that its equivalent diameter is approx. 2 km [27], we can determine its volume: approx. 4.2 km$^3$. It is known that the average volume of FeNi alloy for H chondrites is 8 vol.% [28], therefore the volume of FeNi alloy is 0.34 km$^3$. Kamacite density is 7.85 g/cm$^3$ and taenite density is 7.8-8.2 g/cm$^3$ [21]. For further calculations, the density for the entire FeNi alloy was assumed. After calculations, the mass of FeNi alloy in the considerate asteroid is estimated at approx. 2,650,000,000 Mg (2,650 Mt). Table 7 shows the results of the above calculations. This relatively small near-Earth asteroid has FeNi alloy resources that would theoretically cover Earth's demand for the following metals, iron for one and a half years, nickel for 92 years, cobalt for almost 66 years, and copper for two weeks. However, it should be kept in mind that the data presented in Table 7 are primarily intended to show the scale of potential resources of extraterrestrial bodies. Metals obtained from asteroids will be used primarily outside Earth, where the demand for these metals will be completely different than on Earth.

| Metal   | Potential resources [Mg] | Annual mining production on Earth [Mg] | Theoretical coverage of the Earth’s demand [years] |
|---------|--------------------------|---------------------------------------|-----------------------------------------------|
| Iron    | $2.4 \cdot 10^9$         | $1.5 \cdot 10^9$                      | 1.6                                           |
| Nickel  | $2.3 \cdot 10^8$         | $2.5 \cdot 10^6$                      | 92.0                                          |
| Cobalt  | $9.2 \cdot 10^6$         | $1.4 \cdot 10^5$                      | 65.7                                          |
| Copper  | $7.9 \cdot 10^5$         | $2.0 \cdot 10^7$                      | 0.04 (14 days)                                |

The above calculations are based on many assumptions and theoretical data from reputable publications [21,27-29] but show the rough scale of potential needs. In the next stage of the research, the specific contents of the mineral phases in the FeNi alloy will be determined and the number of meteorites taken for the research will be increased.

5. Conclusions
FeNi alloy, in addition to the obvious iron and nickel, also contains cobalt and copper, which may also be important for mining and industrial activity. Cobalt and especially copper are present in relatively
low concentrations (Co – 0.35%, Cu – 0.03%). However, it should be considered that extraterrestrial resources are primarily supposed to cover the extraterrestrial demand for these metals, to shorten the supply chain and reduce the very high costs of launching and transporting these raw materials from Earth to potential bases and extraterrestrial colonies.

Among the main minerals of the FeNi alloy, kamacite is the most abundant in iron (92.9%) and cobalt (0.38%), while taenite has the highest content of nickel (33.16%) and copper (0.17%). However, it should be kept in mind that at present it is impossible to selectively obtain individual mineral phases of the FeNi alloy and this alloy should be considered together.

A small near-Earth asteroid that is a potential parent body of group H ordinary chondrites, an example of which is (143624) 2003 HM16, may be an object of mining exploitation. It is true that the copper content is not high - in an asteroid with a diameter of 2 km, it is approximately equal to the copper mined on Earth within 2 weeks, but in the case of iron it is already 1.5 years, and in the case of cobalt and nickel it is 65.7 and 92 years, respectively. However, it should be remembered that extraterrestrial mining arises primarily for extraterrestrial needs. These metals will probably be used to create tools or structures close to the place of their extraction. At the moment, it is difficult to predict what the demand and technological possibilities of extraterrestrial mining will be, but we can be sure that they will grow over time. It should also be mentioned that although extraterrestrial mining is not developed with Earth’s needs in mind, the technologies being developed will certainly be used on Earth as well.

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