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Meteoritic matter and materials manufacturing

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ABSTRACT

Purpose: The aim of this paper is to show the correlation between materials science and the study of extraterrestrial matter, especially meteorites.

Design/methodology/approach: Raman Spectroscopy and Cathodoluminescence (CL) are two main methods used by Author to characterize meteorites.

Findings: Understanding laboratory techniques for manufacturing different materials (e.g. diamond) helps to understand the processes taking place in space. Conversely, the new findings and discoveries give new insight applicable to material science and laboratory techniques.

Research limitations/implications: The possibilities of creating new materials similar to those found in meteorites is shown in the paper. For instance diamond polytypes are not yet well characterized and could lead to advances in materials science.

Originality/value: SEM / CL images of DaG 868 presented in this paper are shown for the first time.

Keywords: Meteorite; Materials; Nanomaterials

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SHORT PAPER

1. Introduction

Development of new materials with specified functions is the significant aspect in manufacturing products [1]. Modern society is trying to find a new generation materials with quantifiably exact properties, such as nanomaterials or intelligent materials; this is connected with the development of novel technologies as well. Achievements in materials engineering in 21st century are possible because of interdisciplinary collaboration but it is important to remember that, as in the history of mankind, innovation often comes from nature as well.

Keeping this perspective in mind, meteorites can be treated as the samples from what is perhaps the most amazing and complex laboratory from which we have samples: space.

Progress of our civilization has been governed by the human discovery and mastery of different naturally occurring materials. This aspect of our history is clearly seen in the very way we think about different epochs in human history by materials: for instance, the Stone Age, Bronze Age and Iron Age [1]. But iron was first obtained from meteorites, long before the Iron Age began.

Many tools and artifacts manufactured of meteoric iron have been found by archeologists. These include beads, swords, daggers, and other items. Meteoritic metal can be often identified because of the nickel content or the Widmanstatten figures which can be sometimes preserved even in heavily worked samples (seen at the Figures 1 and 2).

A few examples of objects found by archaeologists to have been made from meteoric iron are mentioned in table 1, showing the first human instances of ferrous metallurgy. These items include 3 balls from the 5th millennium BC found in Iran, the well-known dagger and blades from Tutankhamen's tomb, as well as some others artifacts [2]. Figure 3 shows the hatchet from Wietrzno-Bobrka, Poland, made of meteorite iron [3]. Iron in that times was more precious that gold.

Fig. 1. Iron meteorite Odessa with Widmanstatten figures

Fig. 2. Iron meteorite Gibeon with Widmanstatten figures

Table 1.
Prehistoric objects made of meteoritic iron [2,3]

Object	Approximate date B.C.	Location
3 small, hard, heavy balls	4600-4100	Tepe Sialk, Iran
9 tubular beads	3500-3300	Gerzeh, Egypt
Broken disc, three fragments	2500	Ur, Iraq
Macehead or finial	2400-2200	Troy, Anatolia
Dagger blade, 16 miniature blades; model headres	1340	Thebes, Egypt, Tutankhamun tomb
Hatchet	700-550 B.C.	Wietrzno-Bobrka, Poland

Ernst Florens Chladni was the first scientist to published that meteorites were rocks from space: he did so in his 1794 work entitled *"On the Origin of the Pallas Iron and Others Similar to it, and on Some Associated Natural Phenomena"*. In our present time, new minerals, grown somewhere in space, in much different conditions than those known on or in Earth, are found in meteorites. Often, modern techniques are used to characterize them: microRaman, nanoSIMS, HRTEM, SEM EDS, CL and many more.

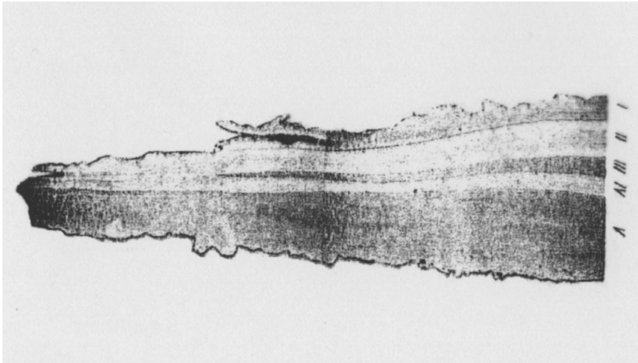

Fig. 3. Iron meteorite hatchet from Wietrzno-Bobrka, Poland, 11.3 cm long, 700-550 B.C. [3]

2. New materials

One such new mineral is chladniite, named after the father of meteoritics, Ernst Chladni. It was found in the Carlton iron meteorite [4]. Another example is tetrataenite, but there are many more [5].

In some cases, these newly discovered phases were later manufactured in laboratories. But the opposite is also possible; The new sulfide chromium mineral Cr_5S_6, was first obtained in a laboratory and was subsequently discovered in nano-mineralogy investigations of the Murchison CM2 carbonaceous chondrite [6]. This shows that scientific discoveries in meteoritics and technological development influence each other.

An interesting is history is that of lonsdaleite – a hexagonal form of diamond first identified in the Canyon Diablo iron meteorite in 1967, synthesized in a laboratory around 1966, and published in 1967 [7,8]. It shows that laboratory technologies and natural discovery often go hand-in-hand.

2.1. Carbon materials

Carbon is a very interesting element. It exists in different allotropic forms: diamond (sp^3 hybridization), graphite (sp^2 hybridization), and carbines (sp hybridization) [9]. However, these three main allotropic forms of carbon allow for a plethora of phases: many types of fullerenes, nanotubes, many diamond polytypes of cubic, hexagonal or rhomboedral symmetry, carbon onions and more [10]. These phases have been found in different meteorites. Diamond is known as a material of extreme properties, it has the highest thermal conductivity, hardness and is chemicly inert in macroscopic level, but nanodiamonds from the other hand, show high level of bioactivity [9]. These are only few interesting properties of diamond.

But do any materials harder than diamond exist? Ferroir eat al. [11] have found, in the Haverö meteorite (a fall in Finland in 1971), ultra-hard carbon crystals, which they characterized with Raman spectroscopy. Haverö is an ureilite. Ureilites are rare type of meteorites named after meteorite Novo-Urei, Russia that fell in 1886. It was the first meteorite in which diamonds were discovered, in 1888. Ureilites are composed primarily of olivines and pyroxenes, with intergranular veins consisting of various carbon phases: graphite, amorphous carbon, diamonds, lonsdaleite, carbides and probably other phases as well [10,12]. Figures 4-7 show the surface of Dar al Gani 868 ureilite type meteorite sample (DaG 868), 40.3 g stone, which was found in the Libyan desert in the year 2000 (SEM BSE CL described elsewhere [10]). Diamonds are clearly seen in high quantity.

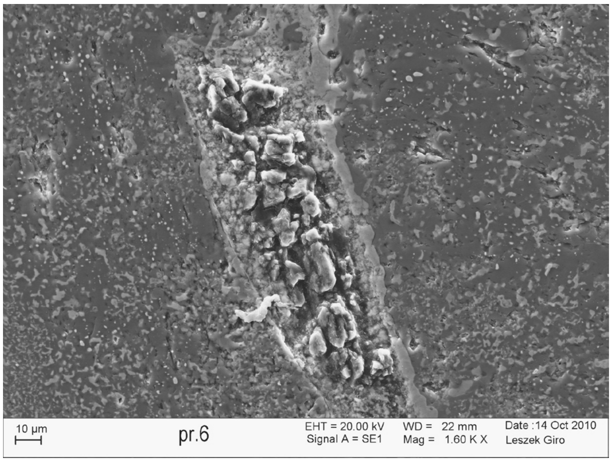

Fig. 4. SEM image of DaG 868 ureilite, carbon-bearing vein at center

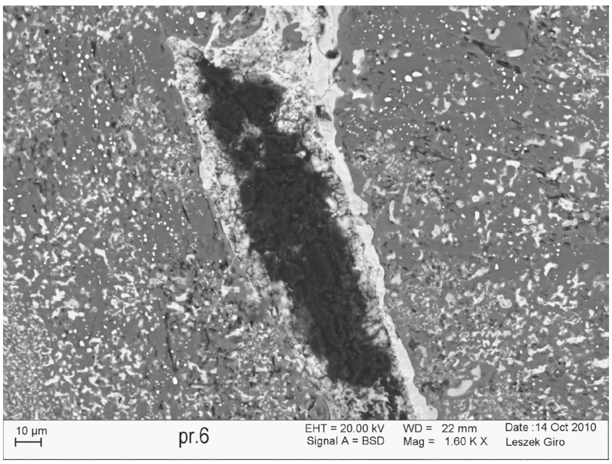

Fig. 5. SEM BSE image of DaG 868 ureilite, carbon vein

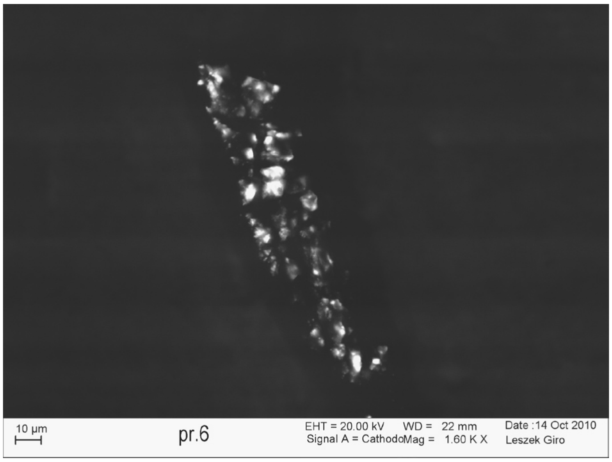

Fig. 6. CL image of DaG 868 ureilite, bright spots are diamonds

Previous Raman spectroscopy research has shown that a high diversity of carbon phases exists in meteorites. Raman band for monocrystalline cubic diamond is a sharp peak at 1332 cm^{-1}. In ureilites broad diamond shifts from about 1300 cm^{-1} to 1340 cm^{-1} are observed. Also, full width at half maximum (FWHM) parameters shows high diversity. This data is more precisely described elsewhere [10,12,13]. These shifts can characterize different polytypes of diamond, but also can indicate internal stresses inside diamonds crystals, different isotopic crystal compositions, and/or smaller crystal sizes (esp. the presence of nanodiamonds). It has been proven that different diamond polytypes such as 2H, 6H, 8H, 10H, 21R, occur in different ureilites. It is important to note that that these “different’ diamonds coexist in very small areas of given samples, in which they are also intermingled with graphite and with the other carbon phases. Studying these meteoritic diamonds could help material science in designing modern carbon materials.

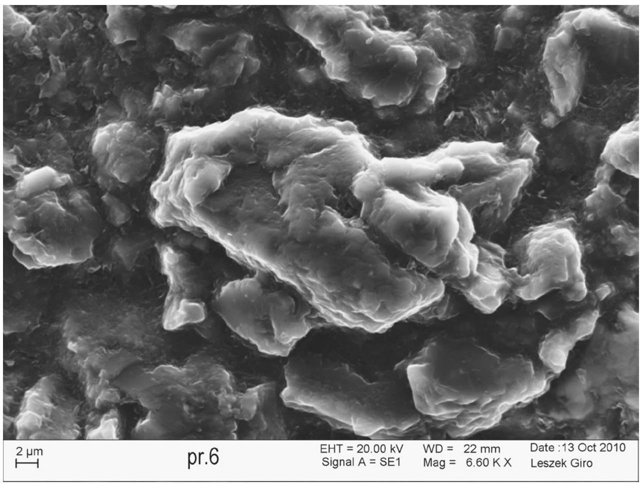

Fig. 7. SEM image of diamonds on the surface of DaG 868 ureilite

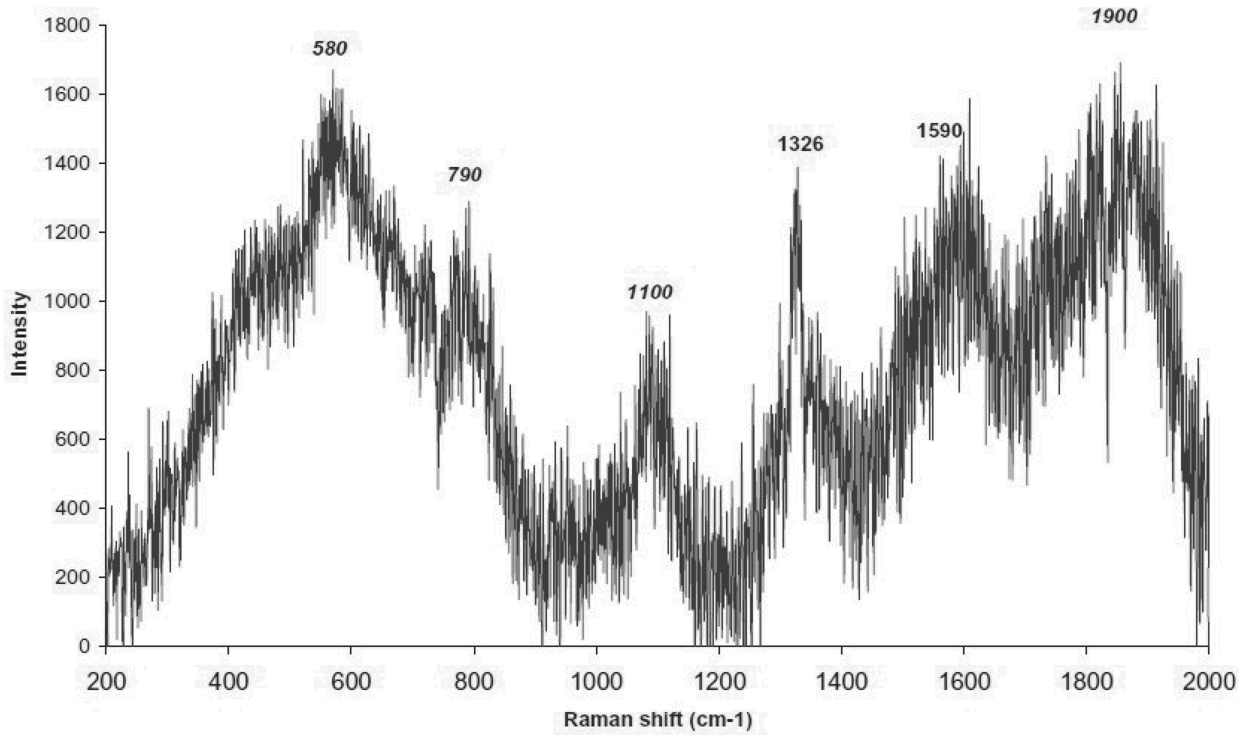

Fig. 8. Raman spectroscopy of presolar nanodiamonds from Allende meteorite [10,19]

Some diamond polytypes are manufactured in the laboratory with different technologies, for instance chemical vapour deposition [14] or by shock compression [15].

There is much debate between scientists regarding the origin(s) of diamonds in ureilites. Answering these questions will help us understand the processes of diamond formation in space which may be similar to in-lab CVD or HPHT (high pressure high temperature) transformation from graphite. In space, these phase transformations may have been facilitated by past collisions [16]. Comparing extraterrestrial materials to those obtained in laboratory experiments can bring insight into the processes that led to the creation of these naturally-occurring materials that must have formed in very extreme conditions [17].

2.2. Nanomaterials

Nanomaterials were a very popular subject for research in this past decade. In this area material science can also learn from space's natural "laboratory." The focus of this paper will be on nanodiamonds as what is perhaps the most intriguing of these materials. Astrophysists have discovered that nanodiamonds exist in space, around stars. Nanodiamonds have been also found in one group of meteorites in particular: carbonaceous chondrites [18]. Some of these diamonds have been called "presolar" nanodiamonds because they were likely formed in a giant star, before our Solar System existed. In laboratories here on Earth, nanodiamonds have been obtained with chemical vapour deposition (CVD) processes, and with detonation techniques [17].

Presolar nanodiamonds have been separated from the carbonaceous chondrite meteorite Allende and described more precisely elsewhere [19]. Carbonaceous chondrites are a very interesting group of meteorites because they represent the most primitive matter from our Solar System: the kind of matter from what our Solar System was formed.

Allende diamonds typically range in size from 2-5 nanometers. Raman investigations show peaks at 580, 790, 1100, 1326, 1590 and 1900 cm^{-1} (Fig. 8).

3. Metallurgy and meteoritics

Scientists in 19th century compared meteorite microstructures with those of steel [20]. In the early 20th century, metallurgists studied nickel-iron meteorites in relation to those seen in low-nickel steels. Perhaps the majority of research on meteoric iron at the time was done with these comparisons in mind.

The Widmanstätten structure of iron meteorites and its implications regarding their formation are of great importance. Widmanstätten structure denotes a geometric relationship and a solid state phase transformation.

Nickel-iron alloys in meteorites are composed of kamacite and taenite (in metallurgy ferrite and austenite). Encyclopedia Britannica describes: *"Widmanstätten pattern- lines that appear* *in some iron meteorites when a cross section of the meteorite is etched with weak acid. The pattern is named for Alois Josep Widmanstätten, a Viennese scientist who discovered it in 1808. It represents a section through a three- dimensional octahedral structure in the metal that is formed of bands of kamacite with narrower borders of taenite, the meshes being filled with a mixture of these two alloys.".*

Fig. 9. Seymchan – pallasite found in 1967 in Russia

Weller and Wegst [21] studied Fe-C Snoeak peak in iron and stony meteorites to understand their thermal history. Petrovic [22] reviewed the mechanical properties of different meteorites. He also indicates the importance of studying such materials because of the possibility of potential asteroids collisions with the Earth and such understanding can give us the possibility to prepare the planetary defense system.

Cooling of iron meteorites is often very slow, about 1-10 K per million years, the rate of this process influences Widmanstätten structure geometry.

3.1. Microgravity research

The influence of microgravity on crystal growth in space was not taken into consideration for many years.

Budka shows in his paper [20] that meteoritic materials can be used to study microgravity solidification phenomena. Nickel-iron and pallasites stony-iron meteorites (Fig. 9) show differences and similarities to natural and engineered materials on Earth. They were probably solidified from a melt under microgravity conditions.

NASA researchers are currently studying the microgravity influence on Widmanstatten pattern formation by examining piece of the 3.9 billion year old Mundrabilla meteorite (found in Australia). It is the longest-running crystal growth experiment [23].

The most probably, Mundrabilla meteorite cooled initially by 500 K per year. This initial solidification was very rapid in geological terms. After that very slow cooling appeared, about 1K per million year. NASA research is focused of growing crystals in microgravity, how these special conditions influence the growth, structure and properties of crystal. Computed tomography was used to study the internal structure of meteorite. Dendrite growth and coarsening processes have been investigated.

4. Discussion and conclusions

In prehistory, meteoritic iron was used for manufacturing tools and was also the inspiration for the birth of metallurgy. Nowadays, meteorites still provide us with inspiration in a similar fashion. Understanding cosmic "technologies" could be especially helpful in designing modern materials. In this paper only a few examples have been mentioned, but many more exist.

New findings in the area of meteoritics have a high probability of leading to the increased understanding necessary to manufacture a new generation materials with desired properties. The few examples described in this paper show the great value of previously made discoveries in this area.

Especially interesting is the study of carbon materials and diamond polytypes in meteorites. Examples of extraterrestrial carbon material's diversity, the study of diamond polytypes and attempted manufacturing and investigation in laboratories may lead materials science to the design of new carbon materials with extreme properties (for instance ultra-hard or with other extreme characteristics).

Also, microgravity research may develop new science concerning crystal growth.

At least in part thanks to meteorites, a new generation of materials with interesting properties will be developed in the near future.

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