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# Meteorite as raw material for Direct Metal Printing: A proof of concept study

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ABSTRACT

Asteroid mining as such is not a new concept, as it has been described in science fiction for more than a century and some of its aspects have been studied by academia for more than 30 years. Recently, there is a renewed interest in this subject due the more and more concrete plans for long-duration space missions and the need for resources to support industrial activity in space. The use of locally available resources would greatly improve the economics and sustainability of such missions. Due to its economy in material, use of additive manufacturing (AM) provides an interesting route to valorize these resources for the production of spare parts, tools and large-scale structures optimized for their local microgravity environment. Proof of concept has already been provided for AM of moon regolith. In this paper the concept of In-Situ Resource Utilization is extended towards the production of metallic objects using powdered iron meteorite as raw material. The meteorite-based powder was used to produce a structural part but further research is needed to obtain a high density part without microcracks.

## 1. Introduction

If the standard of living all around the world continues to increase as it has done the last decades, there will be an ever increasing need for resources. This means that prices for the scarcest resources will rise and that mining of these elements will happen at more and more marginal orebodies. As a result, the cost of mining these elements will rise. At some point in the future, it could become profitable to start mining much richer orebodies on asteroids and ship processed products to Earth. Some of the products mined in space will also be used to support activities in space and include rocket fuel, life support, and raw materials for in-space manufacturing.

Asteroid mining is not a new concept: different aspects have been studied by academia, there is commercial activity in this field and different space agencies have shown interest. Andrews et al. sketch a general overview of an asteroid mining system and discuss the readiness level of different technologies involved. They also discuss the profitability of asteroid mining and conclude that a discounted return on investment of 35% can be expected on a 20 year time horizon [1]. The United States and other countries have recognized the right of private citizens to own resources they obtain from asteroids and non-government organizations are working to develop industry standards to assist in the stability of operations [2]. Probst et al. outline a method for the selection of a mission concept for asteroid mining in Ref. [3]. Other researchers present a novel way to find metal-rich asteroids or calculate how many assay probes will be needed to find an ore-rich asteroid [4], [5]. There is not only academic interest in Asteroid Mining; at least two companies are currently active in this field: Planetary Resources and Deep Space Industries. The recent interest from academia, several companies and space agencies (NASA [6], DLR [3], JAXA [7]) shows that asteroid mining is relevant and has a lot of potential.

Three properties that are key for the successful application of Additive Manufacturing (AM) in aerospace industry are (i) its efficient use of (high value) material, (ii) its potential to manufacture low-weight, high performance, structures and (iii) its potential to manufacture objects locally (factory in a box) [8]. The latter has been touched in several publications where e.g. AM of lunar regolith to support human activities on the moon [9–12] or AM of surgical instruments during long-duration space missions [13] are discussed. The use of AM for In-Situ Resource Utilization (ISRU) has also been considered in the asteroid mining literature [6] but so far, no proof of concept study on this subject has been published. This research provides a proof of concept for laser AM of

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**Abbreviations**

| | |
|---|---|
| AM | Additive Manufacturing |
| ISRU | In-Situ Resource Utilization |
| PGE | Platinum Group Element |
| OERU | On Earth Resource Utilization |
| DMP | Direct Metal Printing |
| SEM | Scanning Electron Microscopy |
| XRF | X-Ray Fluorescence |
| XRD | X-Ray Diffraction |

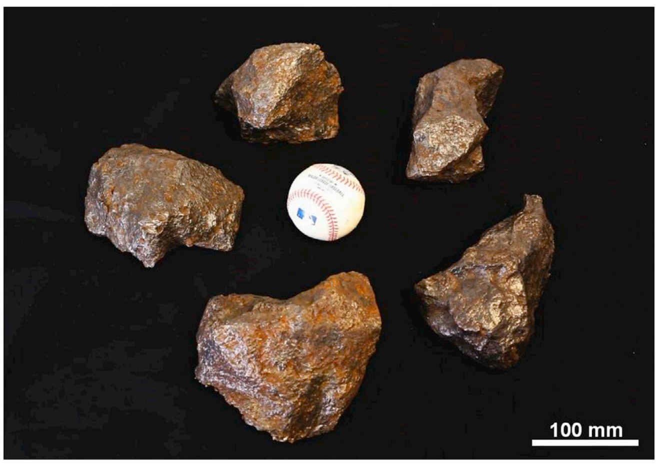


**Fig. 1.** Fragments from the Campo del Cielo meteorite were used to produce powder and a direct metal printed part in this study.

M-type asteroid material by using an iron meteorite as raw material. It is shown that laser AM of this material is possible but further research into optimization of process parameters and chemical composition will be necessary. Future research should also study this material in other production systems, which could be more suitable for in-space use (eg Ref. [14]).

## 2. Materials and methods

The raw material used in this research were fragments from the Campo del Cielo meteorite, found in the 16th century in Argentina, following an impact in pre-history. The bulk composition of the Campo del Cielo meteorite is principally iron (93%), nickel (6%), with cobalt, carbon and phosphorous the last elements present above trace levels [15], [16]. This meteorite type is generally linked to M-type asteroids, the asteroids considered most promising for Fe, Ni and platinum group element (PGE) mining [17]. Fe and Ni are considered for ISRU while the PGEs could be shipped to Earth and used there (On Earth Resource Utilization, OERU). Fig. 1 shows the meteorite fragments before processing.

As the meteorite is of the iron type and thus purely metallic, conventional (developed for metals mined on Earth) gas atomization can be used for powder production. The meteorite was melted in a refractory lined furnace in a research powder production unit at ATI Powder Metals (Pittsburgh, Pennsylvania, USA) and was atomized using Ar gas in a close coupled setup. The same procedures as for terrestrial material of similar composition were followed. All fragments were melted together and were assumed to have the same chemical composition. Generally, powder particles with a diameter smaller than 80 μm are used in the Direct Metal Printing (DMP, laser-based powder bed fusion [18]) process [19]. In this case however, particles with a diameter up to 100 μm were used in order to maximize the amount of powder for production of a proof of concept component [20]. Particles with a diameter smaller than 25 μm were removed by sieving and not used, as these can disturb the deposition of a smooth powder layer.

A customized ProX® DMP 320 machine and DMP Control software (3D Systems, Leuven, Belgium) were used for AM. An extensive review of the DMP process can be found in Ref. [21]. Given the large number of parameters which influence the outcome of the DMP process [22], parameter optimization to obtain fully dense parts would require excessive amounts of powder for this proof of concept study. Therefore, parameter optimization was based on a visual observation of the production process and was halted when a stable process was obtained. The samples described in this study were produced on a steel base plate with a laser power of 125 W, a laser scan speed of 1500 mm/s, a hatch spacing of 100 μm and a layer thickness of 40 μm. The hatch pattern consisted of stripes and was rotated 115° every layer. No preheating of the build plate was used. With these settings, one $10 \times 10 \times 10$ mm$^3$ cube and two 'thin walls' of 1 mm and 0.5 mm width and 10 mm height were produced. The cube was used for metallography and the thin walls were used to assess possible process limitations.

The particle size distribution of the powder was measured by laser diffraction with a Beckman Coulter LS13320 with Tornado Dry Powder System module. The powder flow rate was measured with a Hall flow meter according to the ASTM B213 standard [23].

The laser reflection of the powder was measured with a Perkin Elmer Lambda 950 with integrating sphere. The reference material for 100% reflection was Spectralon (LabSphere). The reflection was measured for wavelengths between 1000 and 1100 nm with a special interest for 1070 m, the wavelength of the DMP laser. The absorption was calculated as (1-reflection) and a commercial grade 1 Ti powder sample was measured as a reference.

Both the powder and the DMP sample were visualized with an FEI XL 40 Scanning Electron Microscope (SEM). In order to study the microstructure of the powder and the DMP part, samples were ground with SiC paper (320–4000 grit) and polished with diamond and colloidal silica suspensions. The powder was etched with Marble's reagent (10 g $CuSO_4$ in 50 ml HCl and 50 ml $H_2O$) and the part with nital (5% concentrated $HNO_3$ in ethanol) to reveal the microstructure. A Nikon Eclipse MA100 microscope was used for imaging.

The overall chemical composition of the powder and part was measured by X-Ray Fluorescence (XRF). A more detailed measurement for the PGEs and some structurally useful elements was obtained by Glow Discharge Mass Spectrometry (Evans Analytical Group, France) for the powder. The lighter elements were analyzed by Instrumental Gas Analysis (Evans Analytical Group, France) for both the powder and the part.

An X-Ray Diffraction (XRD) analysis was carried out for both the powder and the DMP sample using Cu $K_\alpha$ radiation (40 kV and 40 mA) in a Seifert 3003 diffractometer. The diffraction pattern was measured in the 20°–120° range with a step size of 0.02° and for 2s per step. A flat graphite crystal monochromator was installed in front of the scintillation detector to deal with the fluorescent radiation due to the interaction of Cu-$K_\alpha$ radiation with the Fe containing sample. The lattice parameter of the constituent phase was calculated by Rietveld refinement using the Topas Academic software.

## 3. Results and discussion

Fig. 2a shows that most of the powder particles are spherical while Fig. 2b shows that not all particles smaller than 25 μm were removed. This observation was confirmed by the particle size distribution measurement, shown in Fig. 2c. These small particles were present either as loose particles or as satellite particles (attached to the surface of larger particles). The first group reduces the powder flowability by the large Van der Waals forces they cause, the second group causes mechanical interlocking between powder particles. Despite the presence of these small particles, the powder flowed through the Hall flow funnel at