**mars**

**Topical: Additive Manufacturing of Steel on Mars and the Moon Enabled by In-Situ Resource Utilization**

Prof. David C. Dunand 1-847-491-5370 Department of Materials Science & Engineering Northwestern University dunand@northwestern.edu October 31, 2021

**Problem Statement / Abstract**

We seek to couple research on **additive manufacturing (AM) of steel** and on production of **iron from in-situ resource utilization (ISRU)** - as well as from recycling streams – to create lunar, Martian and orbital habitat and transportation system, while achieving drastic reductions in the mass of materials and spare parts to be shipped from Earth as well as improvements in operational safety.

**Relevance of research and topic**

Additive manufacturing (AM) will strongly reduce the need to ship and stock spare parts to maintain any long-term presence in orbit or on Mars/Moon.  Creating the feedstock powders needed for AM via *in situ* resource utilization (ISRU) and recycling will reduce the mass of raw materials and feedstock to be imported from Earth, while providing additional redundancy and safety.

So far, research has focused on reduced-gravity AM of polymers and concrete, but less is known about reduced-gravity AM of metals and alloys, despite their crucial importance for pressurized structures and vehicles. We focus here on steel created via AM from ISRU sources (i.e., from meteorites on Mars and regolith on the Moon) or recycled sources (e.g., from empty rocket stages or broken parts).   This topic also addresses new science challenges, namely the effects of zero- or reduced gravity on: (i) rapid laser melting and solidification of steels, (ii) the flow of metallic powders before and during AM, and (iii) the microstructure and mechanical properties of AM-solidified steels.

**Background[[1]](#footnote-1)**

Outposts and settlements on the Moon, Mars, or in orbit require pressurized habitats as well as pressurized ground- and space transportation systems made from materials with high tensile strength (to minimize mass) and toughness (to resist fracture). Beyond early small outposts, *in-situ* resource utilization (ISRU) and recycling are favored, as the cost of large-scale materials transportation from Earth is prohibitive [1]. Sintered Martian concrete [2], sintered lunar regolith [3], and various metallic alloys extracted from regolith [4] have been proposed for the shells of habitats. Sintered concrete and regolith are relatively weak in compression and brittle in tension and thus unsuitable for pressurized thin shells which are under high tensile stresses. Magnesium, aluminum, and titanium alloys processed from surface oxide ores display good tensile strength and toughness but require complex, energy-intensive refinement and reduction processes. Iron-based alloys (i.e., steels) are excellent candidates for pressurized habitats and transportation systems which are subjected to tensile stresses from pressurized atmosphere or fuel, and from dynamic forces during launch/landing [5]. This is because of steel’s outstanding tensile properties (strength, ductility, toughness, and fatigue resistance) from cryogenic to high temperatures, as well as their extraordinary corrosion- and oxidation resistance, especially when alloyed with Ni and Cr (thus forming stainless steels). Crucial to the choice of Fe-Ni alloys, among the large variety of Fe-based steel, is their ready availability as asteroids in space, or as micro/macro-meteorites on the surfaces of the Moon and Mars. So far, NASA rovers have identified 15 metallic meteorites on Mars, ranging from a few centimeters to over a meter in size, and from tens of grams to hundreds of kilograms in mass [6]. One such meteorite, the Heat Shield Rock (~ 30 cm across and ~ 40 kg in mass, Fig. 1 ) exhibits a binary Fe-7 wt.% Ni composition, as measured by the Opportunity rover *via* a-particle X-ray spectrometry [7]. Most Fe-Ni meteorites collected on Earth have Ni concentrations between 5 and 11 wt.%, with the compositional distribution showing a peak at ~8 wt.%, and a tail between 11 and 19 wt.% [8, 9].



Figure 1: Heat Shield Rock consisting of Fe-7% Ni alloy, discovered on Mars in 2005 by the Opportunity Rover. (Photo: NASA)

Iron and nickel production from lunar rocks is also possible, but it necessitates ore beneficiation, reduction and co-alloying [10]. By contrast, Fe-Ni meteorites are fully reduced to the metallic state and pre-alloyed. This significantly diminishes the energy and complexity associated with in-situ fabrication of metallic objects: a simple melting of Fe-Ni meteorites can be implemented. At that stage, non-metallic mineral inclusions (e.g., oxides, sulfides, phosphides) can be removed by slagging, and further alloying elements (e.g., C and Cr) can be added, followed by casting into ingots and post-processing: hot-, warm- or cold stamping, forging, rolling or extruding. If non-metallic inclusions and elemental impurities can be tolerated in the final product, as-collected Fe-Ni meteorites can be directly processed via the above methods without remelting, further reducing energy requirements; in fact, many early societies cold- or hot-hammered tools and weapons from meteorites without remelting [11, 12]. On Mars and the Moon, meteoritic Fe-Ni alloys could also be atomized into powders or extruded/drawn into wires to create, via additive manufacturing (e.g., powder/wire laser melting [13] or powder extrusion/sintering [14]), complex-shaped objects such as tools and parts for machines or engines. Also, if pure Fe and Ni are needed (e.g., to use Ni in other alloys), meteoritic Fe-Ni alloys can be carbonyl-processed at low temperatures to separate the two metals [15, 16].

An additional impetus for the study of Fe-Ni alloys is the Psyche mission, to be launched by NASA in 2022, which will analyze the composition of the M-type asteroid 16-Psyche, expected to be the exposed Fe-Ni core of an early planetary body [17] or a metal-stony asteroid whose surface is covered with metal by ferrovolcanism from its metallic core [18]. A full understanding of Fe-Ni mechanical properties is crucial for the successful modeling of the early geological evolution of M-type asteroids shortly after they have solidified (as their newly formed Fe-Ni crusts cracked and deformed during their cooling) and of solidified ferrovolcanic lava. The mechanical properties of Fe-Ni alloys are also needed for modeling current M-type asteroid behavior, in the context of their deflection [19], mining [20], or impact [21-23].

**Impact**

We seek to further our understanding, in terms of basic and applied science, of the unique microstructures and properties of additively manufactured steel, as well as the challenges and opportunity of manufacturing steel parts in reduced gravity and vacuum, while using local metallic powder sources (from meteorites, regolith, recycled sources). Also, we envision engineering demonstrations of AM parts, to de-risk their use for lunar and Martian outposts and habitats.

**Recommendations**

The benefits of additive manufacturing (AM) - creating complex, mass-optimized, functional parts from CAD files, in a single step, on demand, and without inventory – are amplified for extraterrestrial applications, given the very high cost of shipping parts from Earth.  AM furthermore enables geometrical complexity in parts and new microstructures with unique properties that can be tailored locally within the part, which are not achievable via traditional methods and provide significant mass savings. Additional benefits are achieved if feedstock powders are not imported from Earth, but rather locally produced from ISRU and recycling streams.

AM encompasses many commercial methods for metals and alloys, e.g., powder bed fusion/sintering, directed energy deposition via powders, wires. Manufacturing issues include heterogeneous, anisotropic microstructure; residual stresses; porosity and cracks; in-situ (over)aging during the process; and strong sensitivity on process parameters and initial feedstock. Given the huge range of variables, AM can only succeed if linked to multiscale modeling addressing heat/mass transport, microstructure (phases, composition, grains), defects (pores, cracks).

We recommend ground and microgravity research as follows:

1. Ground research on additive manufacturing of steel relevant to habitats on the Moon and Mars via powder-bed fusion or via wire fusion AM
   1. From in-situ metal production (using simulants for reduced ores and meteoritic Fe-Ni)
      1. Demonstrate and model powder atomization from Fe-Ni meteorites (Mars), or via reduction of oxide ores (Moon and Mars).
      2. Demonstrate and model AM processing of steel part with these powders
      3. Study their microstructure and mechanical properties
   2. From recycling of steel (e.g., stainless steel) and aluminum alloys
      1. Demonstrate and model powder fabrication via melting and atomization from recycled metal parts (fuselage, broken parts) or from ingot (bulk shipment from Earth)
      2. Demonstrate and model AM processing of metallic part with these powders
      3. Study their microstructure and mechanical properties
   3. Create demonstration items such as hand tools, engine parts, rebar for concrete, brackets for habitat walls, and demonstrate their full useability.
2. Microgravity research on additive manufacturing of steel on parabolic flights and on ISS.
   1. Study and model effect of partial gravity (Moon or Mars - parabolic flights) or microgravity (ISS and parabolic flights) upon powder beds subjected to laser melting, on melt zone dynamics (flow) and solidification.
   2. Study and model the unique microstructures (including defects via tomography) enabled by reduced gravity (Mars, Moon, orbit) and by vacuum (Moon, orbit)
   3. Study the resulting properties (mechanical, thermal) of the AM fabricated materials

**Cross-disciplinarity of topic**

The proposed research is at the intersection of three important topics:

1. **ISRU manufacturing** (from regolith, refined surface materials, or Fe-Ni meteoritic alloys) for habitat building, vehicles, machinery (including life-support and food-production systems), repair and replacement of tools and parts. It strongly reduces the mass of materials to be imported from Earth.
2. **Additive manufacturing**, which drastically reduces the spare part inventory (for existing parts), and allows for rapid fabrication of new parts for buildings, machines and vehicles, without Earth shipment.
3. **Tomographic x-ray visualization** of materials.  The same instruments as CT-scans for patients (likely to be available in habitats) can provide crucial quality control for part/objects created in the AM-ISRU nexus (as in-situ or recycled resources are less pure than raw materials from Earth, and as AM can display many types of defects, such as pores, reducing materials strength).

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1. Text slightly modified from: A.A. Ahles, J.D. Emery, D.C. Dunand, “Mechanical Properties of Meteoritic Fe-Ni Alloys for *In-Situ* Extraterrestrial Structures”. *Acta Astronautica*, **189,** 465–475, 2021. [↑](#footnote-ref-1)