TOWARDS IN-SITU MANUFACTURE OF MAGNETIC DEVICES FROM RARE EARTH MATERIALS MINED FROM ASTEROIDS

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ABSTRACT

We outline how magnetic devices such as electric motors may be 3D printed from rare earth metals extracted from asteroids. We suggest that this presents a viable roadmap to full asteroid material utilization beyond the extraction of water and platinum group metals that are often proposed. We concur that returning such material to Earth is not viable but should be used as space assets – for example, electromagnetic launchers for asteroid impact mitigation and magnetrons for solar power satellites to name two possible applications.

1 INTRODUCTION

Asteroid mining is of great interest for industrial development of the space environment, and indeed, has attracted private sector investment such as Deep Space Industries and Planetary Resources. Encouragingly, the US Space Resources Exploration & Utilisation Act (2015) recognises property claims for material extracted from asteroids. However, the current obsession with water resources is neglecting other valuable asteroid materials – the golden apples - which have direct applications in bootstrapping an asteroid-based infrastructure. Human involvement will require an inordinate mass of infrastructure including that required for life support. Hence, any prospective asteroid exploitation missions will be entirely robotic. Whereas the Moon requires a Δv of 6.3 km/s to land on its surface from LEO, a Δv of 4-6 km/s (nominally 5.5 km/s) is required to reach a near-earth object (NEO); furthermore, for a sample return trip to Earth, lofting to an Earth return trajectory requires a Δv of 3 km/s from the Moon but a Δv of only 1-2 km/s from an NEO [1].

Much interest in asteroid mining has been directed towards the mining of platinum group metals (PG). The two most promising asteroid types for PGM recovery are LL ordinary chondrites comprised of 1-5% Fe-Ni metal including 50-220 ppm PGM and M-type asteroids comprised almost entirely of Fe-Ni metal with 100-300 ppm PGM [2,3]. Despite Pt being a widely used catalyst and desirable for its preciousness, we suggest rare earth metals might be more appropriate target for asteroid mining. Both PGM and rare earth metals plus cobalt, magnesium, niobium, tantalum and tungsten are considered to be critical materials for terrestrial applications. Rare earth metals in particular are of great functional utility, the demand for which on Earth exceeds supply, a situation that is projected to worsen over time. Rare earth elements comprise 15 lanthanides (cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, terbium, thulium and ytterbium) and scandium and yttrium. The most useful rare earth metals include cerium, promethium, scandium, neodymium, dysprosium and praseodymium. In meteoritic material, certain elements are preferentially concentrated [4]: Co, W, Sn and PGM are concentrated in meteoritic nickel-iron; lanthanides (rare earth metals), U and Th are concentrated in phosphates and diopside ($MgCaSi_2O_6$ pyroxene); and Cs is concentrated in plagioclase. However, it is important to note that rare earth elements in meteorites are very low in abundance <0.6% (Table 1). Nevertheless, it appears that stony-iron asteroids are the most appropriate sources of rare earths.

Rare Earth Metal	Abundance in Earth's crust (ppm)	Abundance in stony chondrites (ppm)
Yttrium	22	NK
Lanthanum	30 same as cobalt	0.34
Cerium	64 almost same	0.91

	as copper	
Prasaeo-dymium	7.1	0.121
Neodymium	26	0.64
Samarium	4.5	0.195
Europium	0.88	0.073
Terbium	0.64	0.047
Dysprosium	3.5	0.30
Holmium	0.8	0.078
Erbium	2.1	0.20

Table 1. Selected rare earth metal abundances (adapted from [5])

Our particular interest here is in rare earth metals for high power magnets - $Nd_2Fe_{14}B$ are the strongest permanent magnets although it is possible to replace Nd with other rare earth metals but with reduced magnetism. The strength of rare earth magnets permits miniaturisation but they do not function well above 200°C. Minor amounts of dysprosium and terbium extend their temperature tolerance up to 300°C but SmCo alloys are required for temperatures in the range 300-550°C. The rare earth metals of interest for permanent magnet applications:

(i) neodymium is used in $Nd_2Fe_{14}B$ rare earth permanent magnets, ceramic capacitors, electric motors and Nd:YAG lasers at 1064 nm

(ii) dysprosium is used as an additive to NdFeB magnets to improve temperature tolerance

(iii) terbium is used in NdFeB magnets and in magnetostrictive alloys such as terfenol-D

(iv) praseodymium is used in NdFeB magnets to improve corrosion resistance

(v) holmium is used for the highest power magnets

(vi) samarium is used in high temperature rare earth (SmCo) magnets and lasers/masers

Our goal is to realise a complete in-situ supply chain from raw materials, particularly metals – and rare earth metals specifically - to fully manufactured products. The final products on which we are focused are three ubiquitously useful magnetic devices for space – electric motors, magnetrons and electromagnetic launchers all of which require permanent magnets. The raw materials in which we have a specific interest in extracting from asteroids are iron, nickel, cobalt, tungsten, aluminium and, in particular, rare earth elements which is the primary focus here. We have already addressed the extraction of iron, nickel, cobalt and tungsten from lunar resources elsewhere [6]. We focus on nickel-iron asteroids for the extraction of metals including rare earths, but note that critical resources will also be required from stony asteroids such as silica (for the manufacture of glass and silicone plastics) and from carbonaceous asteroids such as carbon compounds (for the manufacture of silicone plastics) and water (for the manufacture of reductants and oxidants). We suggest that the 12 green chemistry principles are directly applicable to asteroid resource exploitation [7]: (i) prevention of waste is preferable to dealing with waste; (ii) atom economy maximises materials incorporated into the product; (iii) reduced use of hazardous reagents for synthesis; (iv) replace hazardous products with safer products; (v) minimise use of solvents, etc; (vi) maximise energy efficiency at minimum temperatures; (vii) use of renewable feedstock; (viii) minimise use of reagents; (ix) maximise use of highly selective catalysts; (x) design products for degradation; (xi) minimise pollution; (xii) minimise prospects for the incidence of accidents. We propose that a single electrochemical processing method – the FFC Cambridge process – and a single manufacturing method – metal additive manufacturing (colloquially, and henceforth, 3D printing) – suffice to convert rare asteroid material into our desired final products, the electric motor, the magnetron and the mass driver.

2 SURVEYING RARE EARTH ORES

For specific materials, the asteroid must be mapped to locate the specific ores required. Large asteroids can be orbited by orbiters from which multiple sampling penetrators may be deployed to the surface for in-situ spot surveying whilst acquiring subsurface core samples. The aftbody of the penetrator may comprise an ascent stage that ejects and returns to the orbiter which may include a scientific analysis payload of remote sensors and sample analysis instruments. Deposits may be identified through gravity and magnetic surveys from orbit and surface surveys. Mineralogical analysis may be undertaken by reflectance spectroscopy in the infrared range 0.3-5 μm. Reflectance spectra from asteroids are complicated by reddening and shallowing of absorption features due to space weathering processes [8]. Elemental analysis may be more important than mineralogical analysis for ISRU since it directly targets the desired materials. X-ray/γ-ray remote spectroscopy can measure most of the rock-forming elements – Al, O, Fe, Mg, Si, Ca, S, K, Ti, Cr, Mn, U and Th [9]. This may be supplemented by X-ray fluorescence spectroscopy of drilled core samples. Pale rare earth minerals such as bastnaesite and monazite exhibit green luminescence under mercury lamp illumination. However, U and Th measurements can act as direct tracers for rare earth metals.

On Earth, rare earth metals are not rare but are not usually found in concentrated form – they are dispersed in low concentrations ~10-300 ppm with other minerals such as silicates, oxides, phosphates, halides and carbonates. Lanthanides with low atomic number (light) are more abundant than those with high atomic number (heavy). Although we have little data on the nature of rare earth minerals on asteroids, we extrapolate from Earth. On Earth, there are some 270 rare earth minerals of which 43% are silicates, 23% are carbonates, 14% are oxides and

14% are phosphates. However, only four rare earth minerals are commonly mined: (i) bastnaesite ((Ce,La,Nd)CO_3F) is a fluorocarbonate mineral commonly found in association with iron ore (Bayan Obo rare earth mine in China was an iron ore mine with a current reserve of 1.5 Btonnes iron) which comprises 70% rare earth oxide, 98% of which is Ce, La, Pr and Nd, e.g. large deposits in China and USA; (ii) monazite ((Ce,La,Nd)PO_4) is a phosphate mineral found in beach sands which comprise 70% rare earth oxide, 83-95% of which is Ce, La, Pr and Nd with 4-12% Th and minor amounts of U, e.g. China, USA, Australia, South Africa, etc; (iii) xenotime (YPO_4) is a yttrium phosphate mineral found in association with monazite comprising 67% rare earth oxide with reduced amounts of Ce, La, Pr and Nd – it has a higher heavy rare earth metal ratio than monazite; (iv) rare earth hydrated ions adsorbed on clay mineral surfaces (primarily kaolinite) are formed from weathered granite and are the most important source of heavy rare earth elements with up to 60% of which being yttrium oxide. They are unique to China and given their association with granite, they are not expected to be found extraterrestrially. We assume that bastnaesite (rare earth carbonate) and perhaps monazite (rare earth phosphate) are the form of rare earth minerals in NEOs.

3 ORE COMMUNITION & BENEFICIATION

The acquisition of asteroidal raw materials represents a considerable challenge under micro-gravity conditions while controlling the pervasive dust environment. However, we shall not address this aspect here. Excavation of raw material is followed by comminution, beneficiation and thermochemical/electrochemical processing to yield the desired material feedstock. Although comminution is energy intensive, it enhances effective beneficiation which saves energy for chemical processing. Comminution involves crushing material into fine particles preferably into near pure minerals grains - particle grains in rocks are generally mono-minerals so an effective means to separate different minerals in a rock is to pulverise it to sizes comparable to the grain size prior to beneficiation. Much of the surface regolith will have been subjected to natural comminution by continual impact fracturing but this will not have been systematic so comminution will be required. Rare earth minerals such as carbonates or phosphates are roasted at 400-1000°C in air to convert them into oxides and increase their friability. Oxygen can be readily obtained from other metal oxides or water on asteroids. Alternatively, microwave heating can accomplish much the same effect due to nonlinear heating of different minerals especially iron-bearing minerals. Even low microwave power ~100 W may be employed to assist mechanical fragmentation of rock by reducing the requirements for mechanical grinding [10]. The ore may then be crushed using crusher jaws or rollers and grinding in a ball mill and passed through a 100 μm mesh sieve prior to separation. As there is negligible gravity on an asteroid, the material must be transported by low carrier gas pressure such as CO_2 which may be recycled.

Following comminution, one of the most challenging processes is the separation of mixtures of different minerals from waste gangue – an excellent review is given in [11]. Separation requires differences in physical properties – mass/density, surface properties, electrical properties, magnetic properties or elasticity and brittleness. On Earth, most physical separation is based on density but this requires a fluid such as water, most commonly, or air. There are four primary means of beneficiation of rare earth minerals from gangue – gravity separation, magnetic separation, electrostatic separation and froth flotation [12]. On Earth, each mining site imposes its unique requirements for beneficiation and for the Bayan Obo mine, low intensity magnetic separation is followed by high intensity magnetic separation to remove iron minerals though gravity separation with froth flotation has also been successful [13]. Gravity separation separates rare earth minerals from the less dense silicates using jigs, cone separators, spiral concentrators, shaker tables and centrifugal concentrators. For deployment on asteroids, centrifugal concentrators will be necessary to circumvent the lack of gravity. Gravity separation is the process adopted at the Bayan Obo mine to separate silicates and iron-bearing minerals. Hindered settling ratio determines the efficacy of gravity separation: $HR = (\gamma_{RE} - \gamma_F)/(\gamma_G - \gamma_F)$ where γ_{RE}=specific gravity of rare earth mineral, γ_F=specific gravity of fluidic medium (such as water), γ_G=specific gravity of gangue material. As a dimensionless quantity, specific gravity (usually with reference to water) is independent of gravity field. If HR≥2.5, gravity separation is effective but at HR<1.25, gravity separation is ineffective. At 2.5>HR>1.25, gravity separation effectiveness is dependent on particle size – the upper scale can separate fine particles ~0.1 mm but the lower scale is limited to particles ~1 mm. Gravity separation is ineffective at separating very fine particles unless centrifugal separation is adopted (as is the case here). Gravity separation is often used in conjunction with froth flotation followed by magnetic and/or electrostatic separation. For fine particles with poor settling, froth flotation may be necessary and it can be tailored to the unique mineralogy of the deposit. Froth flotation requires a gravitational field with water as a suspension fluid and air for bubbling. It exploits the isoelectric point which predicts the sign of the charge on a mineral surface at a given pH and this determines the adsorption of flotation reagents with specific mineral surfaces. The isoelectric point of different minerals allows minerals to be separated. It has been used to beneficiate bastnaesite from both Bayan Obo and Mountain Pass mines using oleic acid ($C_{18}H_{34}O_2$) or hydroxy naphthyl hydroxamic acid $C_8H_5NO_3$ collector (manufactured through the Angeli-Rimini reaction between an aldehyde and a sulphonamide in the presence of the base NaOH) to float rare earth minerals with sodium silicate (Na_2SiO_3) or alum ($Al_2(SO_3)_4.nH_2O$) depressants to control the pH of flotation by depressing iron minerals and silicate minerals. Different minerals float at different pH. Soda ash (Na_2CO_3) is often used as a modifier and a standard frothing agent (usually an aliphatic alcohol) is also added to stabilise the foam. The complexity of reagents and fluids and complicatioms introduced by microgravity renders froth flotation as inappropriate for extraterrestrial use.

Electrostatic and magnetic separation (Table 2) involve no fluids, and indeed, operate best in a vacuum. Magnetic separation removes either magnetic gangue minerals such as magnetite or concentrates paramagnetic rare earth metals from non-magnetic gangue, e.g. paramagnetic monazite from rutile. Diamagnetic materials are repelled along magnetic lines of force while paramagnetic materials are attracted along the magnetic field lines. Ferromagnetic materials are separated by low-intensity magnetic separators such as drum-type separators; weakly magnetic materials are separated by high intensity magnetic separators such as roll-type separators. For extracting rare earths, roll magnetic separators are usually adopted – high intensity magnetic separation involves magnetic fields ~5000-6000 G requiring rare earth permanent magnets.

Mineral	**Magnetic susceptibility (m^3/kg)**	**Density (g/cm^3)**	**Conductivity (S/m)**	**Sorting voltage (V)**
Magnetite	8000	4.9-5.2	2.78	7800
Ilmenite	1800-4000	5.5-6.0	2.51	7050
Garnet	63	3.5	6.48	18000
Monazite	14	4.9-5.5	2.34	6552
Rutile	0	4.2-4.3	$<10^{-8}$	8000-25000
Quartz	0	2.7-2.8	3.57-5.30	8890

Table 2. Physical properties of rare earth and reference minerals

Electrostatic separation exploits differences in electrical conductivity involving charged drums or belts – xenotime is non-conducting compared with ilmenite which is conducting. Hence, rare earth oxides in rutile minerals may be extracted as a co-product of titanium extraction. Electrostatic separation is only used when alternative methods are not appropriate (such as separation of monazite and xenotime from gangue minerals with similar density and magnetic properties such as ilmenite) as it requires dried finely ground material – it is used on beach sands. Both magnetic and electrostatic separation are suitable for extraterrestrial use.

4 RARE EARTH SEPARATION

Following beneficiation, the rare earth minerals must be thermochemically or electrochemically processed. Although rare earths are found together, their similar physical and chemical properties (due to their similar ionic radii) make their separation from each other difficult. Hence, terrestrial approaches to separation are robust and may be translated to extraterrestrial mineralogy under a wide variety of conditions. The first separation is cerium (light) group (scandium, lanthanum, cerium, praseodymium, neodymium, samarium and europium) rare earths from yttrium (heavy) group (yttrium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, gadolinium and terbium) rare earths. Cerium group double sulphates with sodium and potassium are barely soluble while yttrium double sulphates with sodium and potassium are highly soluble forming a solubility series. Extraction of different rare earth materials typically involves a series of precipitations. Hydrometallurgical processes of dissolution in strong acid or basic solutions selectively dissolve and precipitate metals – the process adopted is dependent on the rare earth minerals and the associated mineral gangue [14]. Rare earth minerals may be dissolved in a hot concentrated solution of NaOH at 140-150^oC. The resultant rare earth hydroxides are filtered and subjected to selective precipitation. Alternatively, the hydroxides may be reacted with HCl to form rare earth chloride solution which may be fractionally precipitated. Apatite which is a common mineral often contains low amounts of rare earth elements (up to 19% by weight) – it is most commonly decomposed using HCl to leach out the rare earth oxides. Rare earth oxides may also be converted into sulphates through the leaching action of hot H_2SO_4 up to 300^oC (acid roasting). The soluble rare earth sulphates are then fractionally precipitated. Fractional precipitation involves selectively removing metal from solution by altering salt concentrations in solution through heating. If rare earths are converted to metal fluoride, they can be reduced to metal by reacting with calcium metal at high temperature to produce reduced rare earth metal and calcium fluoride. The metal is purified by melting *in vacuo*. Solvent extraction is suitable for large-scale processing and involves serially adding specific organic compounds that extracts one rare earth at a time from an aqueous solution of rare earth salts. It uses toxic and damaging organic solvents and has poor rare earth metal selectivity. Ion exchange involves flushing a cation exchange resin with cupric sulphate solution to form an ion exchange resin. Lanthanides passed over the resin displace the cation. To separate out the lanthanides, a solution of EDTA (ethylenediamintetracetic acid) is passed over the resin and leaches out the lanthanides which can be separated out individually. This technique generates a lot of chemical waste. None of these techniques are transferable to extraterrestrial environments due to the complexity of solutions and solution handling in microgravity. Molecular recognition technology has successfully extracted all 16 rare earth elements except promethium from a solution derived from the Bokan-Dotson Ridge in Alaska using solvents [15]. It is based on a solid-state silica gel support to which a metal-selective chelating ligand is tethered. High selectivity is based on lock-and-key chemistry in which the chelating agent binds the metal ion at two or more binding sites acting like pincers. The target ion is then loaded as a solution into a column system. This is followed by a washing cycle with hot water to pass feed solution through the system. Then a small quantity of eluent (commonly sulphuric acid) is passed through to produce a concentrated eluate of the target metal. No organic solvents are used and minimal waste is generated. It was previously used for the separation of PGM [16,17]. This is a promising technology for extraterrestrial use but it still involves the use of fluids. A potential alternative that should be explored is roasting in oxygen to yield rare earth oxides followed by the use of comminution into single mineral grains. Magnetic and electrostatic separation can perform initial separation fractions which are then subjected to high intensity centrifugal separation of sufficient resolution to separate individual rare earth oxide species. Such high-speed centrifuges can implement accurate sorting based on small differences in density. This approach is simple involving a small number of processes, involves no solutions and potentially yields high purity rare earth minerals.

We have addressed the issue of electrolytic extraction of iron, aluminium and titanium from lunar resources using the electrolytic FFC Cambridge process and the extraction of iron and nickel using the Mond process from asteroid material [18]. Similar approaches may be applied to analogous materials of asteroids, but the purification of rare earth materials will require imaginative application of the FFC Cambridge process. The Mond and FFC processes provide the facility for dealing with both reduced and oxidized ores respectively. As the rare earth metals are in oxide form, the FFC Cambridge process [19] may be adopted to yield individual metals from the separated fractions. The FFC Cambridge process yields purified metal particles which may be fed directly into metal additive manufacturing processes – the Mond process output of Fe and Ni may require an additional physical comminution step.

5 3D PRINTING OF MAGNETIC DEVICES

3D printing permits new physical magnet shapes allowing novel and complex magnetic configurations that cannot be fabricated by injection moulding or other moulding techniques such as powder metallurgy. It minimises waste of valuable rare earth materials. Hard ferrites, AlNiCo and SmCo have been used in permanent magnets but have recently been superseded by rare earth magnets. Rare earth materials are extensively used in electric motors (and solar cells) including neodymium, dysprosium and praseodymium. The most powerful permanent magnets incorporate rare earth metals, especially NdFeB which generate a maximum B-field of 1.4 T, high coercivity H above 1000 kA/m and figure of merit B/H exceeding 200 kJ/m^3. Relative permeability measures response to an applied magnetic field, $\mu_r = \frac{B}{\mu_0 H}$. The high magnetic fields offered by rare earth metals permit higher efficiency motors and/or miniaturised devices. Magnetic coercivity is dependent on grain size. The coercivity of NdFeB magnets increases with decreasing grain size reaching a maximum at 250 nm when the grain size equates to magnetic domain dimensions. However, magnetic coercivity decreases rapidly with increasing temperature above 100^{o}C due to the presence of soft magnetic iron. Doping with 5-10% dysprosium maintains coercivity above 2000 kA/m but decreases its room temperature magnetic remanence under 1 T. Soft magnetic properties traditionally require large grains (> 100 μm) – decreasing grain size yields increasing coercivity (increasing magnetic hardness) reaching a maximum at around 0.1 μm. Coercivity then drops with decreasing grain size for nanocrystals ~20 nm and in glassy amorphous materials. The internal microstructure of NdFeB magnets is critical to their functional performance. Traditional magnet manufacturing has a grain size ~10 μm due to oxygen sensitivity (a factor that does not apply on asteroids). Traditional rare earth magnet manufacture is through (a) sintering of a metal powder into a solid followed by cutting into shape but different metals have different melting points; (b) bonding metal powders with a polymer matrix such as nylon followed by injection moulding. Both processes can be adapted to 3D printing: (a) fused deposition modelling (FDM) of 45-65% metal particles into 3D bonded magnets; (ii) laser or electron beam sintering/melting of metal powder. The 3D printed shape is then emplaced in a magnetic field to permanently magnetise it.

Soft magnets may also benefit from rare earth metals. Soft magnetic materials are readily magnetised and demagnetised by virtue of low coercivity (<1000 A/m). Electrical steels are iron-silicon alloys used in electromagnetic cores such as those in transformers and motors with high electrical resistivity. The addition of 3% Si to Fe increases electrical resistivity by a factor of 4. However excess Si beyond 4% embrittles the alloy. Fe-3Si M19 electrical steel is a common solution but Fe-2Si-0.15 Nb offers a magnetically stronger version in which <0.15% Nb suppresses dislocation annihilation and recrystallisation. Fe-based amorphous alloys have high magnetic saturation but also high magnetostriction which is undesirable, but Co-based amorphous alloys with minor Fe addition eliminates magnetostriction at the cost of lower magnetic saturation. Amorphous metals of $(Fe,Co,Ni)_{70-85}(Si,B)_{15-30}$ produced by rapid solidification of the melt form an amorphous glass matrix due to Si and B for soft magnet applications. The addition of Cu and Nb to the melt yields an ultrafine nanocrystalline structure of 10-15 nm FeSi grains with superior soft magnetic properties including a magnetic field saturation of 1.2 T [20]. The optimal alloy composition is $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ (FeCuNbSiB). To control the hysteresis loop requires compensating for magnetostrictive anisotropies by annealing. However, in motor cores, it is desirable to enhance the magnetic permeability along the lamination length (001 direction) - 0.3-0.7 mm thick laminations reduce eddy current paths. This typically requires hot and cold rolling to generate grain orientation. This potentially lends itself to the control of textural microstructure through 3D printing. Non-magnetic laminations may be patterned into magnetic material for motors.

To exploit these capabilities, we are developing 3D printed electric motors, magnetrons and electromagnetic launchers to complete the demonstration of an end-to-end manufacturing capability from mine to off-the-shelf product. The rotary and linear motor and magnetron are magnetic-based devices that can exploit rare earth material and other resources extractable from asteroids. We shall focus on the rotary electric motor. There are several designs of electric motor. In the shunt DC motor, the rotor and stator windings are connected in parallel. In the series DC motor, the rotor and stator windings are connected in series. In the compound DC motor, the stator and rotor windings are connected in parallel and in series. If the series DC motor has laminated stator magnets, it can be run from both a DC or AC supply. In the permanent magnet DC motor, the stator is a permanent magnet without winding. Brushless DC (BLDC) motors are reliant on the electronic control circuitry to generate a rotating magnetic field to drive the rotor – brushless dc motors are not strictly DC motors but are pulsed AC motors. DC motors offer the best performance with an ideal torque-speed relationship but they require commutators - commutators energise the rotor coils at 90^o. AC motors are robust but are more complex to control. In sensorless control, the position of the rotor flux is estimated through Kalman filters or sliding mode control. AC motors include induction and synchronous motors. Induction motors operates by inducing a voltage in the rotor without using brushes. Both stator and rotor constitute rotating magnets. The rotor rotates more slowly than the magnetic field rotation causing slip. Synchronous motors have the stator of an induction motor with a rotating magnetic field and the rotor of a DC motor which synchronises its rotation with the rotating B-field. Synchronous motors are designed to generate constant speed but require squirrel cage windings to be self-starting. Stepper motors are a special case of synchronous motors. Reluctance motors are synchronous induction motors which start like an induction motor and run like a synchronous motor. It comprises a soft magnet rotor magnetised by current energising stator coils. It has six stator coils – three pairs of windings to generate three phase rotating field. The rotor is a soft magnet that is torqued by the stator coils and does not require rotor coils. A potentially 3D-printable pancake motor has been explored experimentally though it was not actually 3D printed [21]. Its chief novelty lay in its flat coil pattern. The motor coils were constructed formed by milling of copper-clad PCB. It employed no soft magnetic material in the rotor which would reduce its inertia but limit its torque capability.

We have opted to 3D print the DC electric motor as all other motors are essentially derived from it. We have initially been concentrating on the motor core (rotor). We have demonstrated several 3D-printed models using our Prusa 3D printer which prints PLA plastic impregnated with metal powder. The Prusa inputs PLA or ABS wire from a spool 1.75 mm diameter which is heated up to 280^oC and extruded through a brass nozzle of 0.4 mm diameter offering a minimum layer thickness of 0.05 mm. Our first rotor was based on ProtoPasta's commercially available magnetic PLA which comprised 50% ~40 μm iron filings by mass (Fig 1a). 3D printed magnets constructed from ProtoPasta have been characterised as magnetically soft with a relative permeability of 1.5, a low coercivity and magnetic saturation <1 T [22]. Our second rotor was manufactured by NRC through polymer additive manufacturing. The rotor comprised 50% iron filings by volume in a PLA matrix. Both offered similar performance indicating a trade-off between the larger magnetic field generated by the 50% iron by volume against its greater weight. NRC also supplied a third rotor with 50% silicon steel particles by volume in a PLA matrix to prevent small detents on startup (Fig 1b).

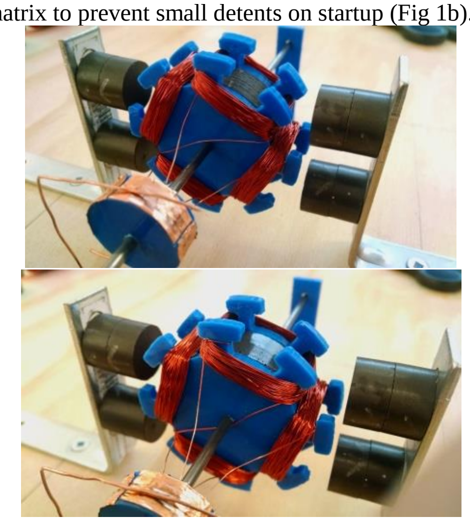

Fig 1. 3D printed rotor: (a) 50% iron by mass; (b) 50% electrical steel by volume

We have photolithographically-printed wiring patterns to replace the wire coils on the rotor. Traditional photolithographically-printed wire patterns in pancake motors require a very large number of soldering points (Fig 2a) but our photolithographically-printed coil design reduced this to four soldering points (Fig 2b).

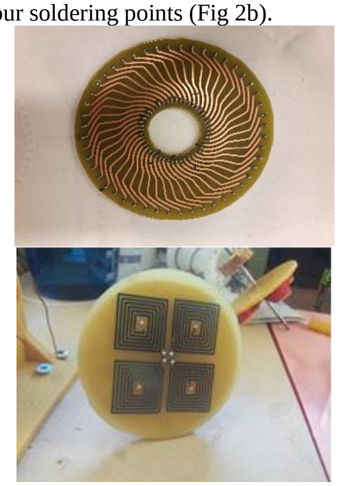

Fig 2. Photolithographically-printed wire coils (a) traditional pancake motor design; (b) our design to reduce solder point requirements

We have successfully tested the printed coil design in a pancake motor test configuration. Our pancake motor comprises three plastic rotor disks with flat coils on both sides of each disk sandwiched together (six sets of coils). The rotor assembly is separated by a narrow airgap on both sides of the rotor. The two plastic stator plates either side of the rotor disk each mount several off-the-shelf rare earth magnets arranged parallel to the rim of the rotor disk (in alternating NS sequence). A central steel axle connects the fixed stator plates to the sandwiched freely rotating rotor disk. Each rotor disk implemented 4 coils on each side in quadrature, each coil loop being a spiral coil which was trapezoidal in shape to maximise the coil surface area. Current was fed to the printed coils via brushes – current flows radially from the disk axis to edge of the disk and back again.

We have yet to successfully 3D printed the stator magnets – several attempts using ProtoPasta and other soft magnetic materials have yielded insufficient magnetic field suggesting the employment of permanent magnets. Permanent magnets with complex shapes of NdFeB powder dispersed in a polymer matrix have been 3D printed through extrusion using a low-cost 3D printer [23]. The 45 μm spherical powder was generated through melt spinning followed by atomisation in an inert gas. They constituted 45-65% by volume in a polyamide matrix selected for its high fluidity to compensate for the viscosity introduced by the particle loading. Once printed, the magnet was magnetised inside a pulse coil with a 4 T applied magnetic field. Binder jetting has been used to 3D print magnets with 46% 70 μm NdFeB powder in a thermoplastic binder [24]. An inkjet printhead passes over a metal powder bed selectively depositing the binder. A new layer of powder is spread and the inkjet binds another layer until the part is complete whence it is cured thermally at 100-150ºC. However, binder jetting imposed limits to metal particle density. Big area additive manufacturing used composite pellets of 65% NdFeB powder in 35% polyamide (nylon) polymer to extrude bonded permanent magnets with a coercivity of 688 kA/m, magnetic saturation of 0.5 T [25]. Nylon has better flow than traditional thermoplastics enabling the higher density metal loading. There are two options for pure metal 3D printing – selective laser sintering/melting (SLS/M) and electron beam additive manufacturing (EBAM). Selective laser melting (SLM) has been used to fabricate NdFeB permanent magnets with enhanced magnetic performance [26]. This is attributed to the quality of the microstructure and versatile shaping enabled by 3D printing. There are five controllable laser parameters: (i) laser power; (ii) laser focus; (iii) point distance; (iv) exposure time; (v) hatching distance. However, different magnetic properties were manufactured by altering two laser parameters – laser velocity and layer thickness. NdFeB-metal composite permanent magnets have been additively manufactured using cold spray permitting tailoring of microstructure to yield different compositions and size distributions [27]. In cold spray, a fine powder of metal is sprayed in a high-speed compressed jet of gas controlled robotically to build up a 3D part layer by layer without the need for a polymer matrix. A pre-mixture of 60-90% magnet particles dispersed in an Al powder matrix was sprayed directly into a rotor accelerated with a high-pressure gas (nitrogen) through a de Laval nozzle at 300-600ºC yielding a magnetic saturation of ~0.25 T. Parts may be additively manufactured with blended physical properties that vary at different locations on the part – such gradient alloys cannot be manufactured through alternative means [28]. The creation of these functionally graded metals such as magnets embedded in non-magnetic material requires considerable control over phase transformations at the interfaces using compositional 3D phase diagrams to smooth the transitional properties between metals. This eliminates the need for joinery between metals such as epoxy or fasteners. Hence, 3D printed electric motors appear feasible.

6 CONCLUSION

These technologies are potentially transformative for space industrialization and asteroid impact mitigation: (a) electromagnetic launchers are based on linear versions of rotary electric motors; (b) flywheel energy storage is implemented through Halbach electric motor configurations; (c) all robotic and manufacturing machines are kinematic configurations of electric motors; (d) magnetrons provide the key component in wireless power transmission and microwave-assisted mineral comminution/beneficiation. Furthermore, these technologies have significant potential for direct terrestrial application for high performance magnets for electric vehicles, efficient wind energy generation, and efficient microwave oven applications on Earth.

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