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DEVELOPMENT OF NEW 3D PRINTED MAGNETIC MATERIALS FOR SPACE APPLICATIONS

EXECUTIVE SUMMARY REPORT

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Introduction

Among the several criticalities for future space exploration and colonization is undoubtedly the supply of raw materials to manufacture every component needed. The utilization of *in situ* resources present on the surface of a moon/planet, as well as secondary raw materials extracted from end-of-life components, represents the only sustainable solution for long-term out-of-Earth permanence.

Moreover, Additive Manufacturing (AM, commonly known as 3D printing) is a new paradigm of manufacturing with unrivalled freedom of geometry and equipment flexibility, which is ideal for low-volume production and customizability required from the Lunar exploration. Indeed, 3D-printing equipment can manufacture any geometry without the need for molds or fixtures specific for a single part, and therefore it is especially suitable not only for *in space* manufacturing but also *on Earth* applications with low production volumes, complex and optimized geometries, and custom high-performance materials. Among the 3D printing technologies, Fused Filament Fabrication (FFF) is a material extrusion-based technique which has been proven to be employable in reduced or zero gravity, and therefore represents the most promising way to additively manufacture component in the space environment. Moreover, Fused Filament Fabrication presents low equipment cost, low material waste and general ease of processing compared to other Additive Manufacturing technologies, and it is thus favorably applied in a variety of *on-earth* applications.

Magnetic materials, both with soft and hard magnetic behavior, are key components in many devices aboard any spacecraft, such as motors, mechanisms, actuators and sensors. The most common route for the manufacturing of magnets is the sintering process, which produces the highest magnetic performance possible but it is energy intensive and requires molds for each geometry. The alternative is the use of bonded magnets, which are composite materials composed of a polymeric matrix with a high content of magnetic filler. Being polymer-based, bonded magnets can benefit from all the manufacturing processes typical of polymers, such as extrusion, injection molding or filament based 3D printing. Therefore, the possibility of manufacturing magnetic components with an Additive Manufacturing process and with materials available in situ is a valuable perspective for the future of space agencies.

Therefore, the aim of this project was to develop innovative composite and nanocomposite materials with soft magnetic fillers processable via Fused Filament Fabrication 3D printing to manufacture brushless motor components for space applications. With the developed materials, a brushless direct current motor was designed via Finite Element analysis to optimize the static, dynamic and electromagnetic performances arising from the mechanical and electromagnetic properties of the 3D printed soft magnets. Finally, a prototype of a motor stator with the optimized design and best performing material was 3D printed as a *proof of concept* of the application on the innovative composite for low power motors in space environment.

Materials development

Based on the resources present *in situ* on the surface of the Moon and in end-of-life electronic components which would be brought from Earth, three soft-magnetic materials have been selected to be used as fillers in the 3D-printable composites:

- Magnetite ($FeO \cdot Fe_2O_3$),
- Nickel-Zinc-based ferrite ($(Ni_xZn_{1-x})Fe_2O_4$),
- Iron Nickel (FeNi) alloy.

As matrix in the composite materials, a high-performance polymer was selected, namely polyether-ether-ketone (PEEK). PEEK presents high mechanical properties, retained even at temperatures as high as 250°C, high glass transition and melting temperatures, and high chemical, wear and fatigue resistance. PEEK is frequently employed as a thermoplastic matrix for high-performance composites, prevalently as long carbon fibre-reinforced pre-preg laminates or as micro- or nano-composites. Due to its properties, PEEK is compliant to the European Space Agency's ECSS standard for space utilization and is therefore utilized extensively in this sector.

The raw materials have been commercially procured and employed to manufacture composite materials with nine different compositions. The raw magnetic powders have been chemically, thermally and morphologically characterized gaining the necessary information to assess the fillers' stability during processing, their morphology and particle size. 3D-printable filaments of suitable dimensions have been extruded and characterized with a number of techniques. The presence of the filler particles did not appear to significantly affect the characteristic temperatures and degree of crystallinity of the filaments, which retains the PEEK matrix thermal properties. The polymeric matrix was found to protect the magnetic fillers from oxidation confirming the processability of the filaments, which are thermally stable up to 580°C. The glass transition temperatures are always in the range 160 – 170°C, highlighting a wide service temperature range. The filaments present increased elastic moduli and reduced ductility with increasing filler content. The developed materials and filaments, with all the compositions, are therefore suitable for 3D-printing.

A 3D-printing process for the developed filaments was setup and fine-tuned using a commercial FFF 3D printer. The fine-tuning was aimed at guaranteeing proper material flow, avoiding printing defects (like warpage, detachment from the bed and clogging of the nozzle due to filler particle build-up) and compromising between resolution and printing time. Test samples and cylindrical magnets were 3D-printed with all the developed filaments.

The morphological and phase analysis on the 3D printed parts highlighted the absence of oxidation of the filler particles during processing and a lack of significant porosity, inter- and intra-layer voids. The 3D-printed parts have been tensile tested to assess their mechanical properties in view of the design of a brushless motor. All the materials presented excellent soft-magnetic properties, with saturation flux densities up to 466 mT, low coercivity and negligible hysteresis dissipated energy. PEEK FeNi-based materials show the best magnetic performances and are the most promising for the final application.

Whereas magnetic, all the 3D-printed parts resulted to be electrically non-conductive, which is a beneficial property for the application in a motor or electromagnet since eddy currents induced in the soft-magnetic materials are widely detrimental to the performance of the system and an insulating material can hinder the flow of current and, thus, the losses.

Brushless DC motor design

Starting from the material properties and design constraints, an axial flux brushless direct current (DC) motor has been designed via finite element analysis. A parametrical mechanical static analysis on different rotor designs led to the identification of a set of compliant rotor designs regarding functional (angular momentum) and material resistance (allowable strength) requirements. Among the compliant designs, the optimal solution was identified as the one entailing the lowest weight, the least severe stress state and the first wobbling mode eigenfrequency furthest from the forcing rotational frequency.

The electromagnetic simulation of the axial flux brushless DC electric motors equipped with traditional magnetic materials led to the identification of an optimal system configuration featuring eight magnetic pole pairs and sixteen coils (two arrays of electrical windings per sector).

The present design was hence analysed to assess the best PEEK-based ferromagnetic material to replace standard soft Iron. In particular, the magnetic properties achieved by all the innovative 3D-printed composite materials have been used as input in the simulation to select the best material and design. PEEK with 85% by weight of iron-nickel alloy resulted in the best electromagnetic performance, with a deliverable output torque of 0.522 N m (against 0.765 N m for standard heavier soft iron, used as benchmark). The torque values obtained by the developed materials are compatible with low power applications such as micro-actuators, pointing devices for small antennas and mini-control moment gyroscopes (mini-CMGs).

Finally, a demonstrator of a brushless DC motor stator, with transversal copper windings and the designed optimized geometry, has been 3D printed with the best performing newly developed material, namely PEEK 85 FeNi. The 3D printed stator demonstrated the proof of concept for this application, opening the possibility to apply this materials in the selected applications.

Conclusions and outlook

In conclusion, the project has successfully:

- Developed innovative 3D-printable composite materials with soft-magnetic properties based on high-performance polymers.
    - The soft magnetic fillers are based on resources available in situ in the perspective of In situ Resource Utilization for the future Lunar colonization.
    - The materials are 3D-printable via Fused Filament Fabrication into soft-magnets with mechanical, thermal and magnetic properties suitable for the application in brushless motor for the space environment;
- Designed a brushless DC motor with optimized geometry employing the developed magnetic composite materials;
- 3D-printed a demonstrator of a motor stator with the best performing composite material.

The foreseen next steps to follow on the work involve the 3D-printing of functional prototypes of a motor stator which can be functionally tested in a real BLDC application in order to further optimize the design or the material.

Moreover, the possibility to 3D-print not only the soft-magnetic materials developed in this project but also hard-magnetic composite materials, developed in a previous work [105], would open the opportunity to manufacture a fully 3D-printed BLDC motor, which would benefit from great advantages:

- recyclability, thanks to the thermoplastic nature of the composites matrix;
- great reduction of losses caused by eddy currents, being the composites generally non-conductive;
- 3D-printability in situ (also in reduced or zero gravity) with no need of specific molds and fixtures for each geometry.