The Electro-Thermal Budget of a Factory in Orbit

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Abstract
The Enhanced Factory for Extraterrestrial Space Technology Operations (EFESTO) project investigates the feasibility of an in-space factory to realize a full recycling chain of space waste. The melting process of debris is a crucial aspect of the recycling chain and requires the development of sophisticated techniques capable of operating in microgravity conditions. The electro-thermal budged of an Electromagnetic Levitation Melting (EML), a viable candidate to assess the melting task, is examined in this paper.

Keywords
Induction heating, electromagnetic levitation melting (EML), microgravity

1. Introduction

The EFESTO (Enhanced Factory for Extraterrestrial Space Technology Operations) project is dedicated to exploring the intricate technological challenges that a prospective space-based factory will confront. Following the workflow of Figure 1, the EFESTO project aims to investigate the feasibility of a factory in space located in the Low Earth Orbit (LEO), implementing the whole production chain of new components, exploring novel Additive Manufacturing (AM) techniques, from the recycling of waste, dismissed satellites, and broken components.

The electrothermal budget of a factory in space is investigated in this paper to assess the melting process of debris. Among all the electrothermal technologies, Electromagnetic Levitation Melting (EML) has gained interest in metallurgy in space processes [1]. An electromagnetic levitation facility has been installed on board the International Space Station (ISS) since 2014 [2]. EML represents a viable solution to address the task of melting metals in space, under microgravity (μg) conditions. Although different technologies can be designed to assess the melting task, this paper investigates a pre-conceptual design of an EML facility that could be installed in the factory-in-orbit.

The paper is organized as follows: in section 2, an overview of the EML process in microgravity conditions is given. In section 3, the thermal problem and the energy requirements are analyzed. A brief discussion is given in section 4, while conclusions are drawn in section 5.

2. Electromagnetic levitation melting

Terrestrial EML for manufacturing highly pure materials has been studied for many decades [3, 4, 5]. Conversely to ground experiments at 1 g where strong levitation fields are required to counteract the gravitational force, under μg conditions, experienced inside the factory in orbit, the EML process is particularly simplified making this technology a viable solution to assess the melting process in the EFESTO workflow drawn in Figure 1. EML is not a new concept in the context of electrothermal

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processes in space. Indeed, the ISS has been equipped with an EML facility in the European Columbus module since 2014 [2, 6, 7, 8, 9, 10].

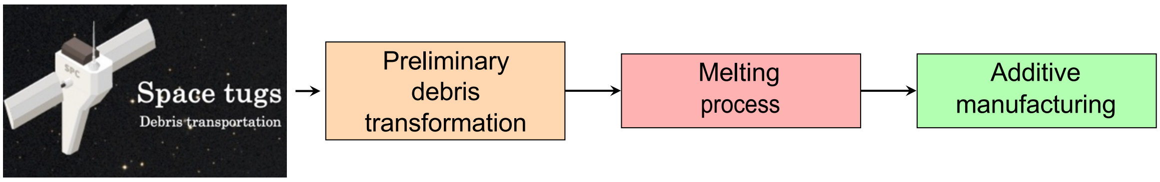

Figure 1: Simplified workflow of EFESTO project for the recycling of debris.

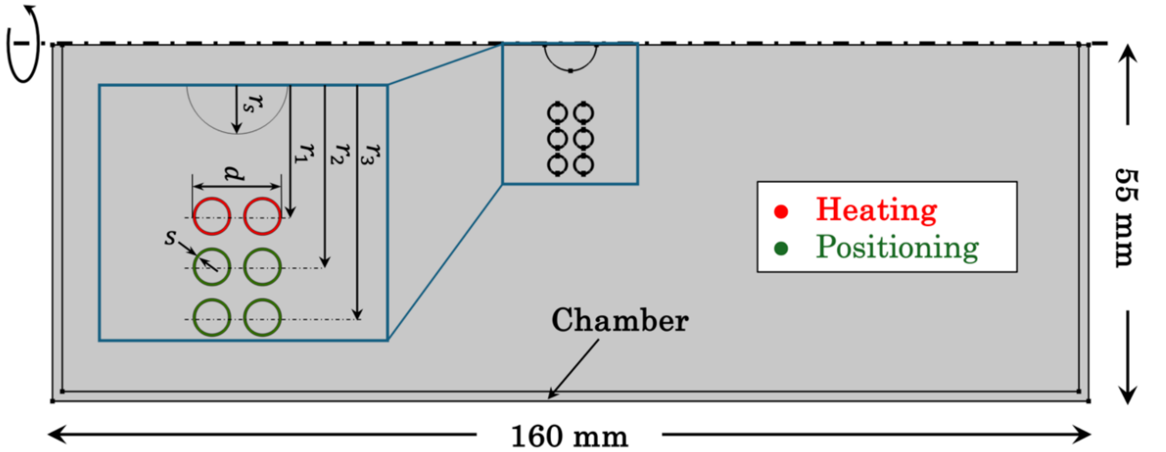

Figure 2: 2D axisymmetric model of the EFESTO-EML. The following parameters for the coil system are used: r_1 = 10.5 mm, r_2 = 14.5 mm, r_3 = 18.5 mm, d = 7 mm. The sample radius is r_s = 4 mm, while the coil radius is 3 mm with a thickness s = 1 mm.

Besides the EML facility, the ISS has been joined with an Electrostatic Levitation Furnace (ELF) [11, 12, 13] whose development started in 1993 by the Japan Aerospace Exploration Agency (JAXA). The major advantage of ELF, which is based on the Coulomb force, is the possibility of handling a broad range of materials if compared to EML, such as ceramics. However, a high-speed real-time feedback control system is mandatory [14]. An extended description concerning the EML and the ELF on board the ISS can be found in the book [1]. A remarkable advantage of EML and ELF techniques, making them very attractive for metallurgical processes, relies upon the absence of the crucible; thus, the contact of the molten sample with container walls is avoided, resulting in less contaminated materials. In this section, a preliminary investigation has been carried out concerning a pre-conceptual design of an EML facility, hereafter termed EFESTO-EML, which could be installed in the factory in orbit to assess the melting task. The layout of EFESTO-EML presented here is for preliminary considerations and is subject to potential changes during subsequent project phases.

The analysis is based on the axisymmetric model reported in Figure 2. Even if the EML facility is generally composed of many modules, e.g., for the power supply and diagnostics [2], here only the functional block, where the electromagnetic levitator and the sample are located, is analyzed. The system is enclosed by a stainless-steel chamber, which operates at ultra-high vacuum conditions. Similar to ISS-EML, the system consists of heating and positioning coils. The former are used to provide the heating power to the sample, while the latter are used to control the position of the sample, which is subjected to the Lorentz force density [N/m^3] written as:

$$\mathbf{f}(\mathbf{r}) = \Re\{\mathbf{J}(\mathbf{r}) \times \mathbf{B}^*(\mathbf{r})\}. \tag{1}$$

In (1), $\Re\{\cdot\}$ takes the real part, * is the complex conjugate operator, while $\mathbf{J}(\mathbf{r})$ is the induced current density in the molten sample, and $\mathbf{B}(\mathbf{r})$ is the magnetic flux density.

From an operational standpoint, a notable divergence exists between EFESTO-EML and ISS-EML. Specifically, EFESTO-EML is designed without the anticipation of human presence on board, thus mandating comprehensive process automation. This distinction underscores the imperative of integrating supplementary coils within EML techniques, enabling the movement of samples along varied levitation paths within the chamber.

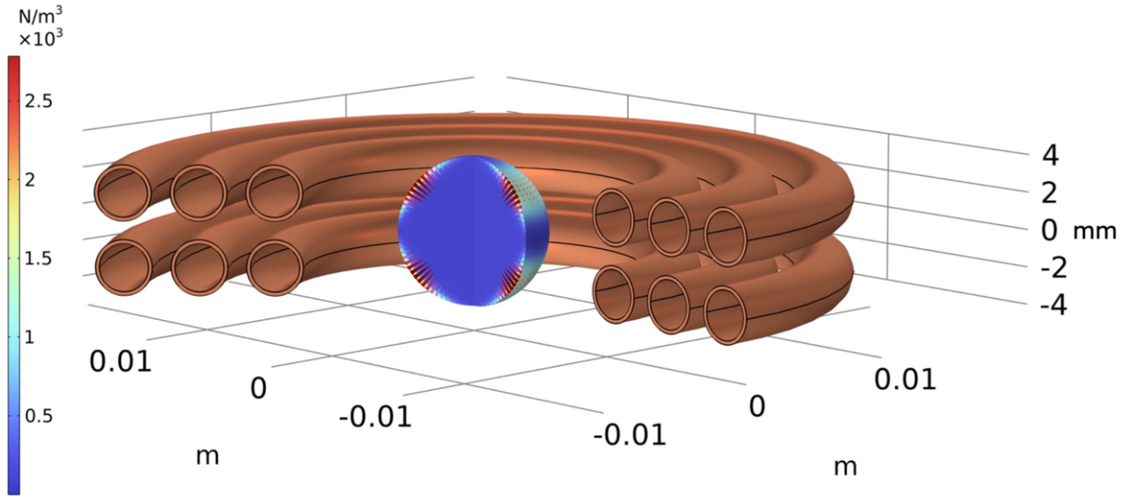

Figure 3: Numerical results of axisymmetric EML modeling in COMSOL®. Force density distribution due to positioning coils.

In the same fashion as the ISS-EML, the position coils made of copper are supplied with a current of 145 A at a frequency of 140 kHz. The thickness of the coils, s, is taken in such a way that $s/\delta \geq \pi/2$, where δ is the penetration depth in the coil, resulting in s = 1 mm. The sample is assumed to be a spherical droplet with a radius of 4 mm. In the following, the finite element method (FEM) software COMSOL® Multiphysics has been used to evaluate the electromagnetic forces by using the *Magnetic Fields* (mf) interface based on the magneto-quasistatic approximation in the frequency domain. The result of the numerical simulation is reported in Figure 3, where the electromagnetic force density exerted on the sample is highlighted.

3. Thermal problem and energy requirements

The power consumption of the recycling chain, in particular, the melting process of debris, as indicated in the workflow of Figure 1, is strictly related to the amount and type of materials to be reconditioned, and the environmental conditions inside the factory. In this respect, Table 1 summarizes the materials of interest for the recycling process within the EFESTO project. In what follows, only the recycling of Aluminum alloys, e.g., the Al2219 (electric conductivity of σ_s = 1.75·10^7 S/m), is considered. The Al2219 sample of spherical shape has a radius of 4 mm (≈ 0.7 mg).

The environmental conditions inside the factory can be argued by considering the following operational scenario:

- The factory will be located in LEO; thus, the external part is subjected to a temperature variation of approximately 300 °C, from -150 °C to 150 °C. In what follows, perfect thermal insulation is considered between internal and external parts, and the ambient temperature inside the factory can be estimated by looking at the typical operative temperature ranges for the more critical subsystems shown in Table 2, resulting in T_{amb}=10 °C.
- The baseline scenario of the EFESTO project does not foresee the presence of crew onboard, therefore it is not strictly necessary to pressurize the ambient. This allows the possibility of operating in “vacuum” conditions; thus, the effect of air advection can be neglected in the thermal problem. The thermal radiation boundary condition is the only mechanism responsible for the heat exchange.

A thermal model has been developed in COMSOL®, by using *Heat Transfer* (ht) physics, to estimate the energy required to reach the melting temperature (in the range 543/643 °C) of the Al2219 sample. The electromagnetic problem is firstly resolved by supplying the hating coils with a current of 210 A at a frequency of 380 kHz, following the ISS-EML [2].

Table 1
Materials of interest for the recycling process within EFESTO.

Material	Type
Aluminum alloys	Al2219 or Al7075
Standard polymers	Nomex® or Kevlar
Technopolymer	ULTEM™ or PEEK/PAEK

Table 2
Typical temperature range for critical subsystems.

System	Temperature range
Avionics	0/50 °C
Chemical propulsion	10/40 °C
Batteries	0/30 °C
Optical sensors	-10/40 °C

Table 3
Energy and power for melting process of a 4 mm-radius sample of Al2219.

Quantity	Value
Total power P_{tot}	90 W
Power on the sample P_s	17 W
Total energy	3600 J
Energy on the sample	680 J
Electric efficiency η_e	0.18

The electric efficiency η_e of the system is evaluated at this stage resulting in η_e = 0.18, being the power on the sample of $P_s \approx$ 17 W and the total power of $P_{tot} \approx$ 90 W. It is worth noting that the copper coils must be actively cooled during the operation. For the thermal problem, *Surface-to-Surface* radiation is added to the sample surface and the inner surface of the chamber, while *Surface-to-Ambient* radiation is imposed in the outer boundary of the chamber. The heat source is provided by the power delivered to the sample P_s. During the phase transition, the material properties of the sample may change, thus, a Gaussian model for the heat capacity is adopted:

$$C_p(T) = C_{solid} + \frac{E}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(T-T_c)^2}{2\sigma^2}\right) \quad (2)$$

where C_{solid} = 0.864 J/(g°C) is the specific heat capacity in the solid state, E = 390 J/g is the energy for phase transformation, σ is the standard deviation and $T_c = T_i + 0.5(T_f - T_i)$ is the melting temperature. T_i = 543 °C and T_f = 643 °C are the onset and completion melting temperatures. The time integration stops at t = 40 s, when the temperature T_f in the sample is reached. The results of the simulation are listed in Table 3, reporting the power and energy required by the EML system for the melting process of a 4 mm-radius sample of Al2219.

4. Discussion

In the EFESTO project, efficient debris separation before the melting process is crucial due to its high level of automation. This involves the use of sorting techniques, currently in the process of definition by other research teams collaborating within the EFESTO project. Additionally, discussions are underway regarding the potential for a two-step melting process to reduce impurities, particularly non-metallic substances, within the samples. This step is imperative for ensuring the production of highly pure materials required for AM processes (if needed). The energy demands of the EML system necessitate the utilization of in-situ technologies, such as photovoltaic panels. However, scaling up to large-scale EML facilities with substantial production rates (i.e., kg/h) introduces additional challenges, not only for the feasibility of the EML process but also from an energy point of view. These challenges are not addressed in this preliminary work.

Furthermore, security concerns within the EML facility are not within the scope of this work, which focuses solely on the processes. However, it is paramount that these issues are thoroughly addressed in future activities to ensure the reliability of the final design. It is noteworthy that EFESTO involves multiple research teams, necessitating collaborative discussions with partners to address various needs effectively.

5. Conclusions

In this paper, initial explorations into the thermal budget of the EFESTO project have been conducted, with a specific focus on the installation of an EML facility. In Section 2 a simple scheme of EFESTO-EML has been described. The simple electromagnetic model presented here will be extended in future research activities to incorporate the fluid motion inside the molten sample, through a magnetohydrodynamic (MHD) simulation [7, 15]. Due to the high level of automation within the factory-in-orbit, a set of moving coils (e.g., for the casting process) is required, and their design will be of interest in future activities. The thermal budget analyzed in Section 3 relies on certain assumptions regarding the operational conditions and dimensions of the space factory. However, at present, these parameters are not yet defined within the project. A key aspect to be investigated in future research campaigns concerns process scalability. The effectiveness of the scrap recycling chain requires the processing of waste of different sizes, much larger than the samples described in the previous paragraph. This reflects the need to implement a process for large-scale EML [16, 17] in microgravity conditions.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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