

## Preliminary study on localized microwave sintering of lunar regolith

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### ABSTRACT

The pioneering objective of a permanent outpost on the lunar surface requires the development of technologies for in situ resource utilisation. Consolidation of lunar soil into products is imperative to avoid unaffordable transportation burdens. The paper addresses the feasibility of the Local Microwave Heating effect as a promising technology for sintering lunar regolith based on microwave radiation, with a simple solid-state generator requiring a relatively modest amount of energy. Experiments were conducted using terrestrial simulants with physical and chemical properties similar to those of lunar regolith. Laboratory equipment with a purpose-built microwave actuator was designed and manufactured with “Design for Embarking” in mind. Experiments have demonstrated the feasibility of the proposed technology with a reasonable degree of confidence. Solid artefacts were obtained with proper setting of microwave parameters and appropriate scanning strategy, proving the feasibility of regolith sintering with a localised microwave source. A roadmap for future development of the technology has been established.

### 1. Introduction

Interest in human colonisation of the moon has grown up in the last decade following the development of NASA’s Artemis missions [1] and ESA’s EL3 project [2]. The Artemis missions include, for example, the development of a base camp on the lunar surface and a lunar orbital gateway. As for the construction of facilities on the lunar surface, one of the biggest concerns is the excessive cost of transporting building materials on the moon. As an example, shipping material on the International Space Station (ISS) can cost roughly 20,000 €/kg, depending on the launch cost [3]. To get the same material to the moon, the cost could be an order of magnitude higher compared to transporting it to the ISS. So it is clear that the solution cannot be to bring materials from the Earth, but to look for building materials on the lunar surface itself [4]. A current focus of research is the use of materials already present on the moon to facilitate the realisation of lunar installations for human life as well as the installation of equipment: this technique is commonly referred to as “In Situ Resource Utilisation” (ISRU) [5]. According to this approach, the “regolith”, i.e. the material of the lunar soil, could be used to create solid structures. Reliable bricks and other mechanically stable components, for example for shielding purposes, made from regolith

would enable the construction of a permanent lunar base and avoid extremely expensive transport of large and heavy components from Earth. Equally promising, analysis of samples taken on the lunar surface has confirmed that the lunar regolith contains up to 40 ÷ 45 per cent oxygen by weight, chemically bound as oxides in the form of minerals or glass. The possibility of extracting such oxygen by an electrochemical process offers a further advantage in terms of obtaining a gas useful for human life with an added bonus of converting the regolith into useable metal alloys. Products obtained from regolith would thus open numerous possible advantages.

The consolidation of the regolith into dense and mechanically stable components would enable the construction of a platform to alleviate the severe problem of lunar dust (the fraction that is less than 30 µm in diameter [6]). In parallel, the production of solid but more porous components would be functional to obtaining anodes that can be used to release oxygen in electrolytic processes with molten salts. Several techniques have been proposed to turn lunar regolith into mechanically stable components [7]: thermal spraying and hydrogen layering [6], furnace sintering under vacuum [8], laser based additive manufacturing [9] and other Additive Manufacturing (AM) techniques [10], and solar light-based sintering with sunlight [11,12]. Many of them suffer from

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**Table 1**

Comparative chemical composition of DNA-1, JSC-1 and the Apollo 14 lunar sample 14163. LOI = loss on ignition.

Oxide	DNA-1 (Wt%) [27]	JSC-1 (Wt%) [28]	Lunar Soil 14163 (Wt%) [29]
SiO <sub>2</sub>	41.90	47.71	47.30
TiO <sub>2</sub>	1.31	1.59	1.60
Al <sub>2</sub> O <sub>3</sub>	16.02	15.02	17.80
Fe <sub>2</sub> O <sub>3</sub>	14.60	3.44	0.00
FeO	0.00	7.35	10.50
MgO	6.34	9.01	9.60
CaO	12.90	10.42	11.40
Na <sub>2</sub> O	2.66	2.70	0.70
K <sub>2</sub> O	2.53	0.82	0.60
MnO	0.21	0.18	0.10
Cr <sub>2</sub> O <sub>3</sub>	0.00	0.04	0.20
P <sub>2</sub> O <sub>5</sub>	0.34	0.66	–
LOI	0.00	0.71	–
<b>Total</b>	<b>98.80</b>	<b>99.65</b>	<b>99.80</b>

**Table 2**

Composition of the simulants used for the sintering tests.

Simulant	Composition	Granulometry
<b>DNA1_V</b>	65% DNA-1 35% DNA-1V	<250 μm
<b>DNA1_V_I</b>	53% DNA-1 35% DNA-1V 12% Ilmenite	<250 μm

limitations related to excessive energy consumption or equipment that is too heavy, making transport to and use on the Moon quite impractical.

A promising technology for lunar sintering of the regolith is based on microwave radiation. Microwave heating and sintering has emerged in recent years as a new method for sintering a variety of materials: alumina powders [13,14] and ceramics in general [15] as well as metals [16,17]. Microwave sintering has shown significant advantages over conventional sintering methods, in fact, microwaves enable a volumetric heating, without the need to heat other external devices (e.g. oven's walls), reducing the power consumption [18].

However, the conventional magnetron and confined working chamber configuration, used in most of microwave-heating systems [19], is heavy and unsuitable for aerospace applications. Furthermore, this type of system is mainly used to post-treat a powder agglomerate obtained by other means [20,21], not as a direct manufacturing process.

The use of Local Microwave Heating (LMH) and compact solid-state microwave sources instead of magnetrons could reduce the size, weight, and operating voltage and improve the spectral characteristics, tunability and controllability of microwave devices [22]. Due to the significant energy concentration in a relatively small area, the LMH effect can be implemented with a relatively low power. To meet the weight restrictions, a promising solution is the use of a microwave generator using semiconductor technology and an open-end electrode. The LMH requires neither a cavity nor a closed chamber and can be obtained with a solid-state generator [19]. The LMH effect can be spatially directed and intensified by a suitable concentrating applicator, such as an open-end electrode or by localized susceptors [23]. The use of microwaves to sinter the regolith would enable ISRU and increase the possibility of realizing reliable large structures on the moon. However, the Technology Readiness Level (TRL) of the technology in existing literature could be estimated in TRL 2 and very little data is available.

Modelling work [24] has identified the key thermal, electrical and magnetic properties of regolith that determine sintering behaviour, including density, thermal conductivity, heat capacity, electrical conductivity, permittivity, and permeability. A lunar regolith simulant is defined as a material made from natural or synthetic terrestrial or meteoritic components to simulate one or more physical and/or chemical

properties of a lunar rock or soil [25]. Carpenter, in a paper dealing with the development of Standardized Lunar Regolith Simulant Materials [26], has identified the most important characteristics of an ideal simulant, namely fidelity and homogeneity.

Purpose of this paper is to report the design and construction of a LMH system optimized for embarking and use on the moon, and to discuss the first experimental validation of the feasibility of this solution to sinter a regolith simulant.

## 2. Materials and methods

### 2.1. Simulants

Regolith simulants were developed starting from the DNA-1 simulant, described in Ref. [27]. This simulant is a cost-effective alternative to JSC-1 [28] and CAS-1. The DNA-1 simulant has a reference chemical composition that can be considered in the useful range for representing the lunar soil in low-Ti mare zones, similar to the Apollo 14 lunar sample 14163 [29] (Table 1).

Previous experiments on magnetron microwave sintering have shown that the DNA-1 simulant has good coupling with the microwave source [30]. It was also found that the artificial addition of Ilmenite, which in practice adds Fe<sup>2+</sup> to the whole, causes better coupling and thus facilitates the heating of the material by the energy of the microwaves [30].

Starting from DNA-1, two simulant formulations were produced to increase the fidelity of the study to a wider range of regolith characteristics and to verify the effects on the sintering performance. Specifically, a glassy phase of DNA-1 (namely DNA-1V) was added to the simulants to mimic the glassy particles produced by meteoric impact [31,32]. In the second simulant, ilmenite was added to verify a better coupling with microwaves [33]. Both simulants were prepared with a granulometry of less than 250 μm. Specifications are given in Table 2.

### 2.2. Sintering system

A system was designed to deliver microwaves locally and precisely to a powder bed located in an environment with a pressure of 0.01 mbar. Although the pressure on the lunar surface is  $3 \cdot 10^{-12}$  mbar [34], a pressure level of 0.01 mbar represents a good compromise between the need to avoid an extremely long test duration and a first reliable check of the effects of vacuum on the sintering process. Before choosing the pressure level for this study, the mean free path for air molecules at 0.01 mbar was calculated to 10 mm [35]. This value was considered as a reference to compare with the distance between anode and cathode in the system to be developed. If the vacuum level is high enough that the molecules are further away than the electrode gap, then it can be assumed that there are no electrical discharges. Section 2.4 provides details on the breakdown voltage according to Paschen's Law, which justifies the choice of the test pressure.

The sintering system was composed of the following equipment.

- Vacuum chamber: the chamber had internal dimensions of 625 x 400 x 600 mm, to accommodate the Computer Numerical Control (CNC) system and equipment for the process. A rotary vane vacuum pump was used to bring the pressure down to 0.01 mbar.
- Microwave generator: a solid microwave generator LEANGEN-2450M-500-M was selected (LeanFA, Bari, Italy). The Microwave Generator (MWG) can emit radiant energy at a frequency between 2400 and 2500 MHz, tunable in steps of 1 MHz. The power can be adjusted from 1 to 500 W with a step of 1 W. During emission, the reflected power is also measured.
- Radiofrequency (RF) cables and accessories: to bring the radiation to the end user (the antenna), special RF cables with an impedance of 50 Ω were used, together with adapters and a feedthrough to guide

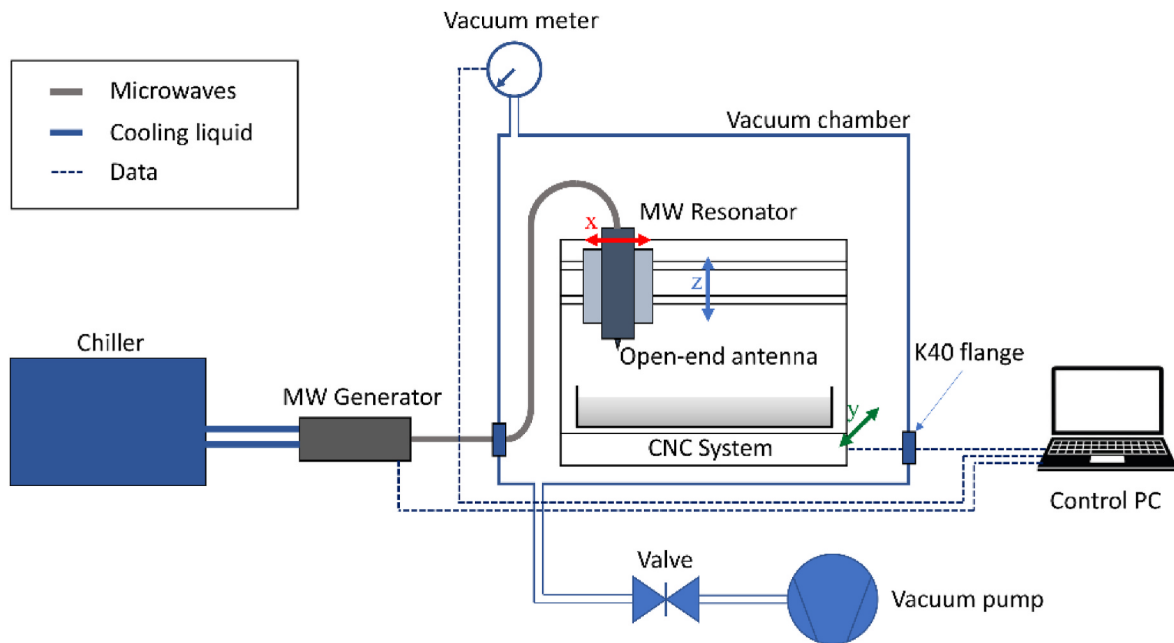


Fig. 1. Scheme of the sintering system setup.

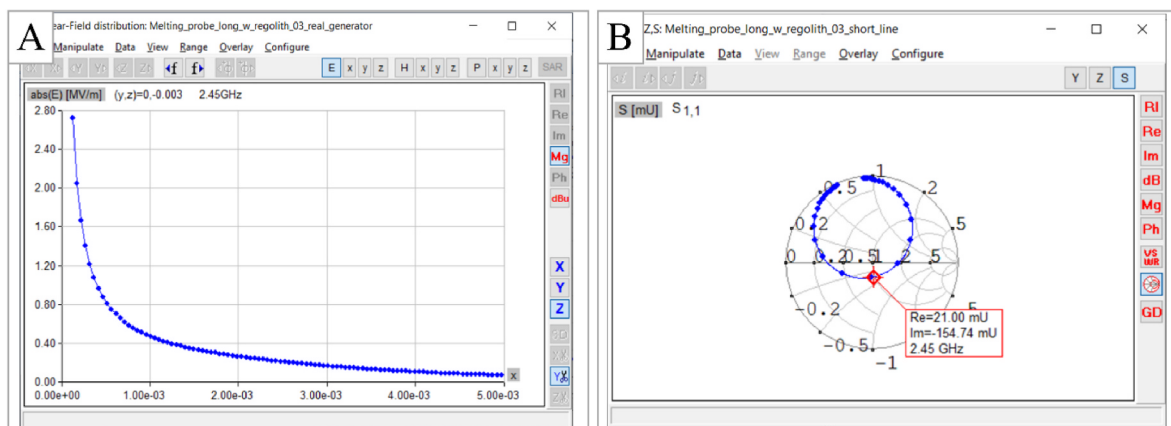


Fig. 2. Diagrams of a) Intensity of the electric field near the needle tip, b) Reflection coefficient looking into the needle (Smith chart), for resonator + needle system.

the radiation through the chamber. The entire transmission line had an impedance of 50 Ω.

- d. Antenna: the aim of this equipment was to bring the radiation precisely onto the powder bed, with the highest possible efficiency. To achieve sufficient efficiency, the antenna included a resonator to match the impedance of the line. More details about the development of the antenna and the resonator are provided in section 2.3.
- e. CNC system: a compact and easy-to-use CNC system was chosen to enable controlled motion of the antenna during the localized sintering tests. A 3018 PRO DIY was used, controlled by a GRBL [36] compatible motherboard. On the platform, regolith powder was enclosed in a container with dimensions of 50 x 50 x 20 mm (x, y, z).
- f. Camera enabling an on-line monitoring of the processes in the chamber.

Fig. 1 shows a scheme of the sintering system. A specific software was in-house developed for the operation and control of the system.

### 2.3. Probe design

The goal was to design and produce a probe for melting lunar

regolith, in a small region on the surface of a powder bed, using microwave heating at 2.45 GHz. The idea is similar to that presented in Ref. [19], where the principle is used for drilling. A needle with a sharp tip is energized by a microwave generator. The tip of the needle is placed on the top of the material. Near the tip, the electric field is very strong and the material is heated by dielectric losses. The nominal impedance of the transmission line is 50 Ω and the available power can be selected in the range of 1–500 W. If the impedance of the load is different, part of this power is reflected and is not available to process the material. In order to improve the matching and increase the excitation of the needle, a resonator (the microwave counterpart of a resonant electric circuit) was used. The resonator was developed using the transmission-line technique instead of the waveguide technique to reduce the space required and keep the antenna small and light. The transmission line consisted of a tungsten rod and a shield. The shield could have a circular cross section. In this case, one would obtain a coaxial-line. In this study, a rectangular cross section was chosen to the aim of easier machining. The resonator length was approximately a quarter-wavelength. The resonator was short-circuited at the top and open at the bottom (where the tungsten rod protrudes into the regolith). The inner conductor of the coaxial-line was connected to the inner conductor of the resonator

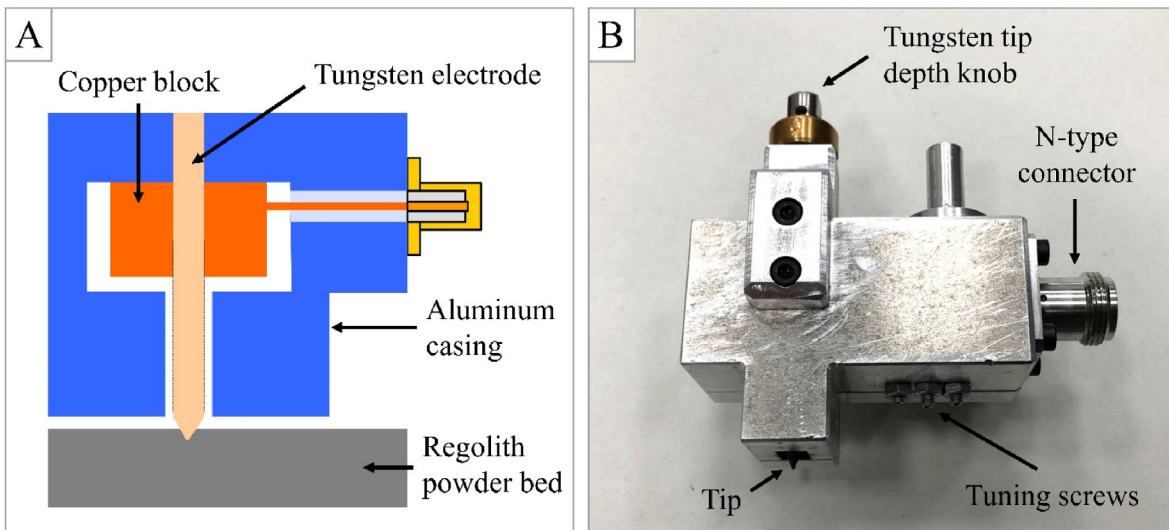


Fig. 3. a) Scheme of the final design of the antenna, b) Manufactured antenna.

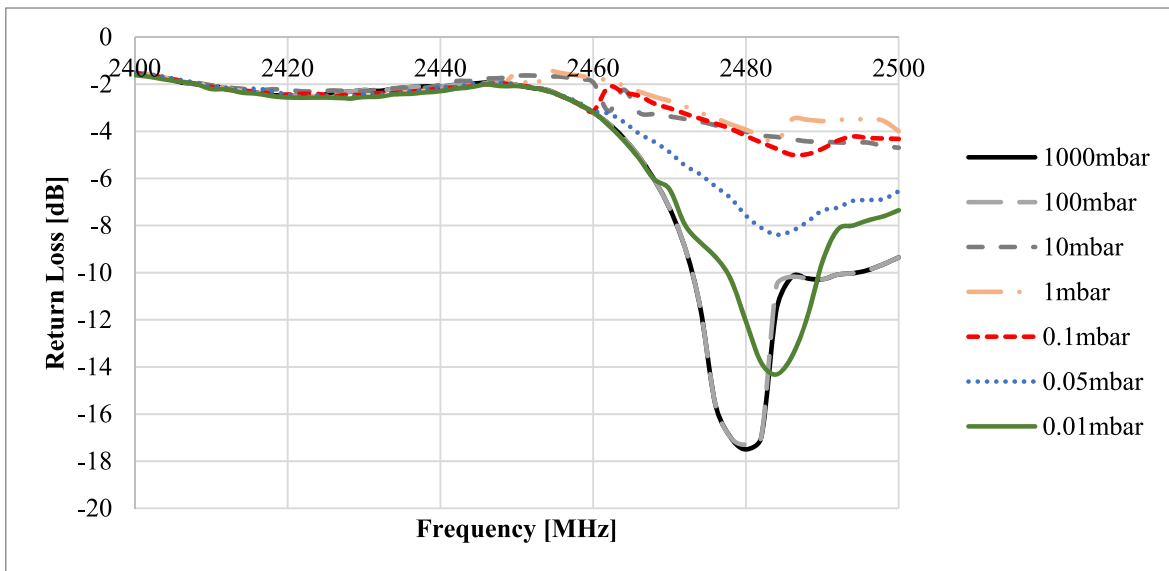


Fig. 4. Plot of return loss vs. frequency of the antenna system at varying chamber pressure values.

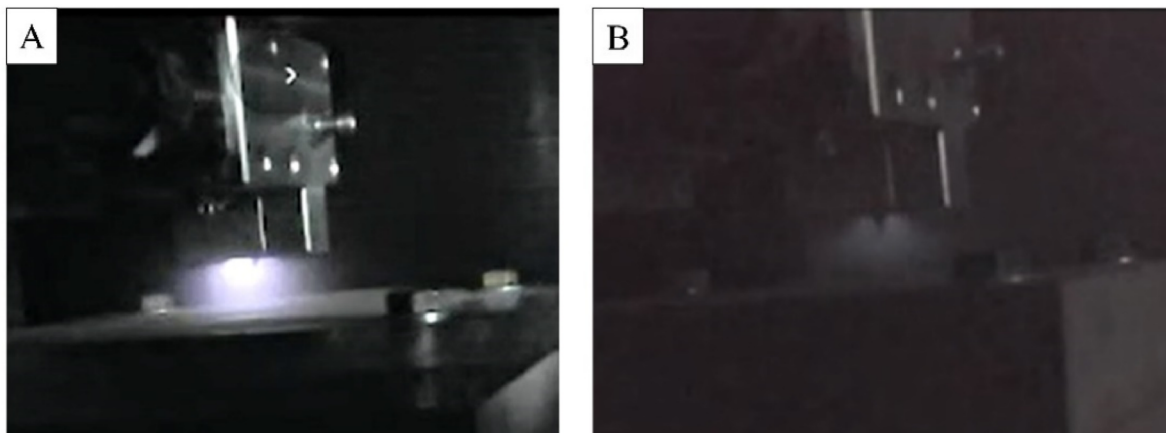


Fig. 5. Discharge around the antenna tip: a) random discharges with high energy dissipation, b) coaxial discharge appearing at low pressure.

**Table 3**  
Process parameters set for tests at room and low pressure.

Room pressure tests					
Forward Power [W]	60	70	80	90	100
Sintering Time [s]	1	10	100	—	—
Low pressure tests					
Forward Power [W]	30	50	—	—	—
Sintering Time [s]	10	—	—	—	—

(shunt feed).

Fig. 2A shows the calculated intensity of the electric field in the final version of the probe. The software used is CST (Dassault Systemes,

Vélizy-Villacoublay, France). The field is about four times stronger than in the pure needle configuration, and it is close to the breakdown field in air at room conditions. Fig. 2B shows the reflection coefficient. The probe is very well matched at 2.45 GHz, where the modulus of the reflection coefficient is close to  $-16$  dB.

The final version of the antenna is shown in Fig. 3. The design is chosen according to the considerations of the simulated model and considering manufacturing constraints.

#### 2.4. System operation

Preliminary experiments in air at room pressure were used to verify the system operation and define a window for the process parameters.

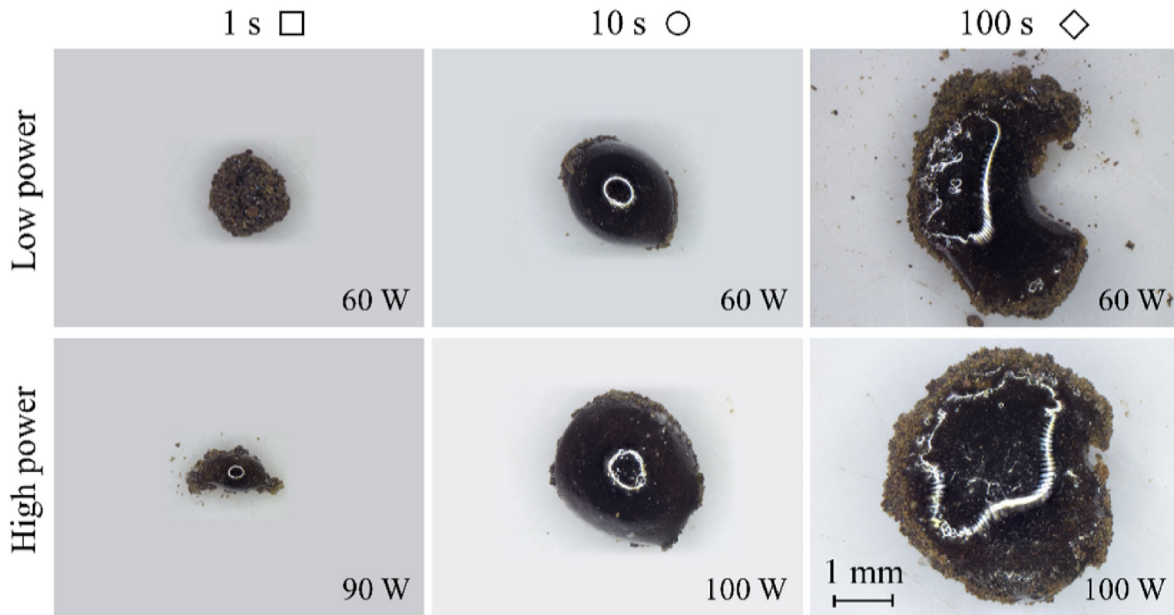


Fig. 6. Microscope images of the samples obtained at different sintering time and power using DNA1\_V simulant. The symbols next to the sintering time identify the simulant-sintering time combination in the plot of Fig. 8.

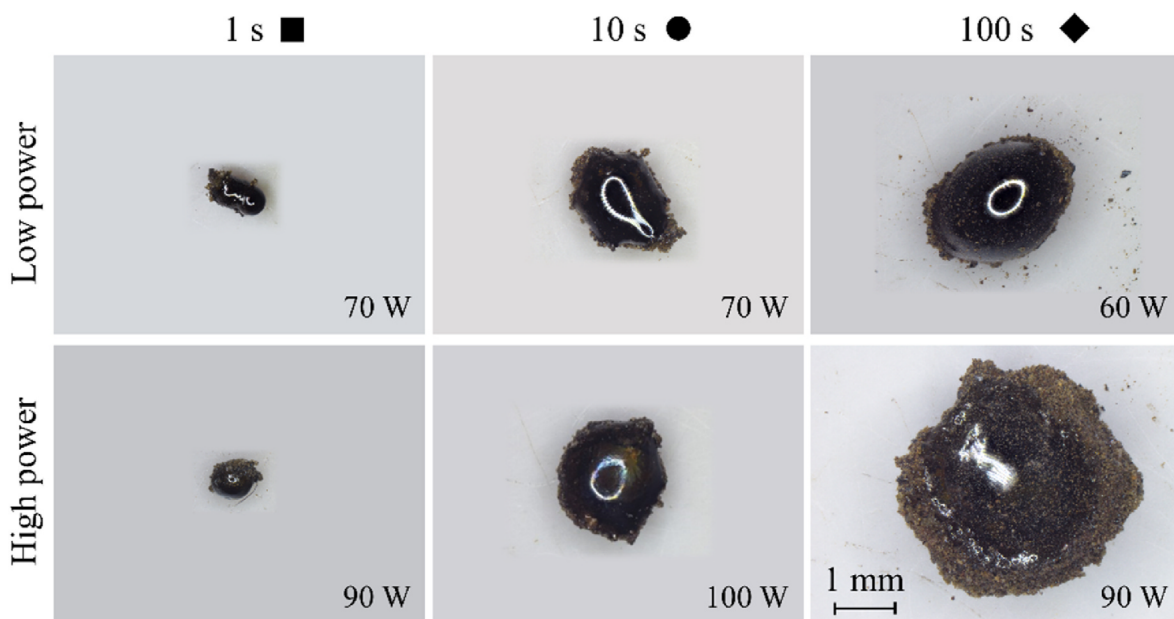


Fig. 7. Microscope images of the samples obtained at different sintering time and power using DNA1\_V\_I simulant. The symbols next to the sintering time identify the simulant-sintering time combination in the plot of Fig. 8.

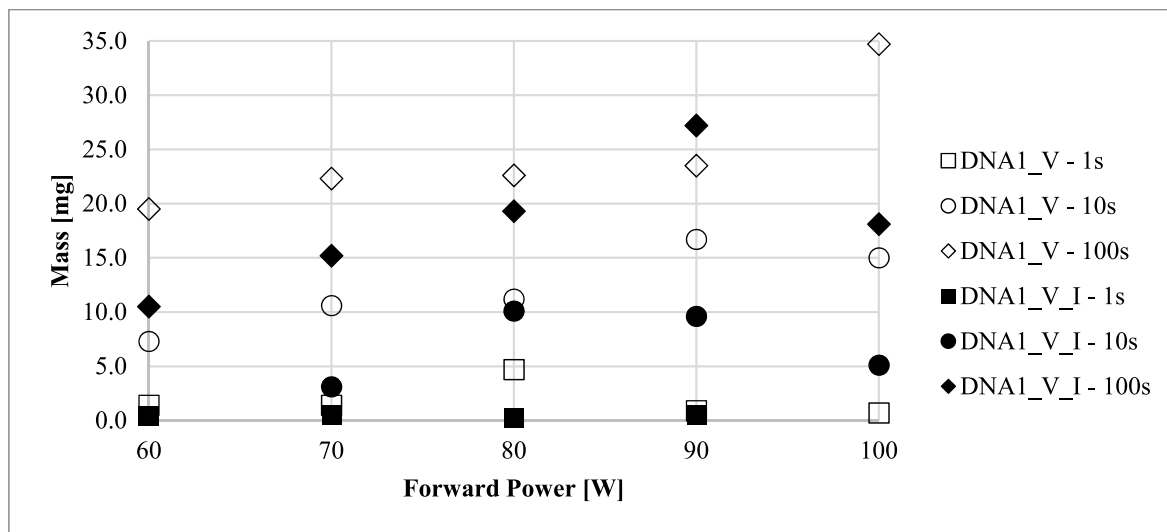


Fig. 8. Mass of the samples resulting from the tests performed at various power and sintering time.

Table 4

Detailed results of the mass and dimension measurement of the samples obtained at room pressure.

Simulant	Sintering time [s]	Forward power [W]	Mass [mg]	Eq. diam. [mm]	Simulant	Sintering time [s]	Forward power [W]	Mass [mg]	Eq. diam. [mm]
DNA1_V	1	60	1.4	1.308	DNA1_V_I	1	60	0.4	0.933
DNA1_V	1	70	1.4	1.602	DNA1_V_I	1	70	0.5	0.7515
DNA1_V	1	80	4.7	1.644	DNA1_V_I	1	80	0.2	0.835
DNA1_V	1	90	0.9	0.903	DNA1_V_I	1	90	0.5	0.696
DNA1_V	1	100	0.7	0.565	DNA1_V_I	1	100	-	-
DNA1_V	10	60	7.3	1.666	DNA1_V_I	10	60	-	-
DNA1_V	10	70	10.6	2.146	DNA1_V_I	10	70	3.1	1.550
DNA1_V	10	80	11.2	2.146	DNA1_V_I	10	80	10.1	1.763
DNA1_V	10	90	16.7	2.826	DNA1_V_I	10	90	9.6	2.111
DNA1_V	10	100	15.0	2.430	DNA1_V_I	10	100	5.1	1.820
DNA1_V	100	60	19.5	2.920	DNA1_V_I	100	60	10.5	2.144
DNA1_V	100	70	22.3	2.944	DNA1_V_I	100	70	15.2	2.362
DNA1_V	100	80	22.6	3.214	DNA1_V_I	100	80	19.3	2.560
DNA1_V	100	90	23.5	3.414	DNA1_V_I	100	90	27.2	3.020
DNA1_V	100	100	34.7	3.836	DNA1_V_I	100	100	18.1	2.604

The forward power of the microwave generator was chosen in a range where it was possible to achieve sintering/melting of the material while avoiding the formation of electric arcs. In fact, due to the proximity of the anode and cathode in the antenna, electric discharges occurred frequently during the tests, resulting in a huge loss of energy. This phenomenon led to a limitation of the maximum forward power to 100 W. The sintering time was chosen in exponential steps: 1, 10 and 100 s. Preliminary tests showed that 1 s was sufficient to produce a small agglomerate while heating for a period longer than 100 s did not result in a significant increase in the mass/dimensions of the solidified bits.

Preliminary tests were also performed at low pressure. In order to understand the behaviour of the microwave system below room pressure, a plot of the return loss versus frequency was experimentally obtained for different pressure levels (Fig. 4). In detail, with the forward power set at 50W, a frequency sweep from 2400 to 2500 MHz was performed, with a step size of 2 MHz. For every frequency step, values of the reflected power were collected for 3 s and the average was calculated.

The return loss (RL) indicates how much power is reflected (i.e. sent back to the generator) compared to the forward power that is delivered by the generator. It is calculated as in Eq. (1). Low values indicate a high power available for the sintering process, i.e. a high efficiency of the system. For this reason, for the success of the sintering process it is critical to set the frequency that minimizes the return loss.

$$RL [dB] = -10 \log_{10} \left( \frac{\text{Forward power}}{\text{Reflected Power}} \right) \quad (\text{Eq. 1})$$

From the plot in Fig. 4 it can be noticed that, while the RL shows a clear minimum at room pressure, the RL always remains above -5 dB when the pressure is lowered to 10 mbar, and it is not possible to identify a marked minimum in the curve. This situation indicates that most of the forward power is reflected back to the generator. In this configuration, a bright random discharge phenomenon can be observed around the tip of the antenna, with variable intensity and position and no discernible direct correlation with frequency (Fig. 5A).

This behaviour changes when the pressure is reduced below 0.05 mbar, and a clear minimum point is observed in the RL curve. At pressures between 0.01 and 0.05 mbar, slight discharges are still seen, but the emitted light is always coaxial with the tip (Fig. 5B). This emission mode is more stable than the random discharges, which explains the stable RL curves below 0.05 mbar.

This behaviour seems to correlate with Paschen's law [37], which states that the breakdown voltage decreases with decreasing pressure below room pressure. At a low vacuum, Paschen's curve shows a minimum, at which the occurrence of uncontrolled discharges becomes very likely. As the pressure is further reduced, the problem of discharges becomes less critical as the breakdown voltage increases. Looking at the behaviour of the resonator, tests at pressures above 100 mbar are likely