



Effects of Post-Printing Sintering Temperature and Atmosphere on the Microstructure and Mechanical Properties of Direct Ink Written Lunar Regolith Simulant

Yingyu Chen¹, Ailing Xun², Lu Zhang^{1*}

¹ College of Construction Engineering, Jilin University, 130026 Changchun, China

² Department of Civil and Environmental Engineering, University of Canterbury, 8140 Christchurch, New Zealand

* Correspondence: Lu Zhang (lu_zhang@jlu.edu.cn)

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Abstract: Direct ink writing (DIW) provides a means of fabricating geometrically controlled components from lunar regolith simulants (LRSs), but the mechanical performance of printed structures depends strongly on subsequent thermal consolidation. The effects of sintering temperature and atmosphere on the relationship between microstructural development and mechanical properties remain insufficiently established for DIW-fabricated regolith materials. This study investigates how post-printing sintering conditions affect dimensional stability, microstructure, and mechanical performance in DIW-printed LRS specimens. Cubic specimens were fabricated using the Jilin University (JLU) LRS and sintered under vacuum or argon at peak temperatures of 1050, 1060, 1070, and 1080 °C. Mass loss and directional shrinkage were measured, compressive tests were performed, and microstructural changes were examined by scanning electron microscopy. The argon-sintered (AS) specimens showed a progressive increase in compressive strength with temperature, whereas the vacuum-sintered (VS) specimens reached their highest mean strength at 1070 °C before declining at 1080 °C. At 1080 °C, argon sintering produced the highest compressive strength (13.35 ± 1.58 MPa) and Young’s modulus (334.43 ± 42.32 MPa) among the sintered specimens. The maximum mean directional shrinkage under this condition was 7.39%. Microstructural observations showed more continuous interparticle bonding and locally fused regions in the AS specimens at 1080 °C, while larger and more heterogeneous pores were observed after vacuum sintering at the same temperature. These results indicate that sintering atmosphere influences the balance between particle consolidation and pore development, with consequences for the mechanical response of DIW-printed regolith structures. The study establishes an experimental basis for selecting post-printing thermal processing conditions for LRS components within the investigated temperature range.

Keywords: Lunar regolith simulant; Direct ink writing; Post-printing sintering; Sintering atmosphere; Microstructural evolution; Mechanical properties

1 Introduction

With the rapid advancement of human lunar exploration programs, establishing a sustainable long-term lunar base has become a central objective within the broader context of deep-space exploration [1]. Such a base aims to support prolonged human activities and enable the utilization of in-situ lunar resources to reduce dependence on Earth-based supplies [2]. However, the unique lunar environment, characterized by high vacuum, intense radiation, and drastic temperature fluctuations, poses significant challenges for the development of construction materials and technologies suitable for lunar applications [3, 4]. The incompatibility of conventional construction approaches with these lunar conditions, coupled with the prohibitively high cost of transporting construction materials from Earth to the Moon, has underscored the urgent need for advanced technologies that enable the efficient utilization of lunar resources [5–7].

In-situ resource utilization (ISRU), which aims to exploit locally available lunar resources as construction feedstock, has been widely recognized as a fundamental strategy for sustainable lunar habitation and development, reducing reliance on material transportation from Earth while improving resource efficiency [8, 9]. Among various ISRU strategies, additive manufacturing (AM), also known as 3D printing, has emerged as a promising approach

for fabricating structural components under extraterrestrial conditions. By utilizing locally available lunar regolith, AM can reduce the demand for Earth-supplied construction materials while enabling precise control over material placement and structural geometry. These advantages further facilitate the rapid fabrication of complex geometries required for lunar base applications [10, 11]. In particular, extrusion-based 3D printing approaches, such as direct ink writing (DIW), offer an efficient route for fabricating complex structures through the layer-by-layer deposition of lunar regolith [12].

Compared with optically based 3D printing processes that rely on low-viscosity resins and complex support systems, DIW is less sensitive to gravity variations, offers favorable process stability under lunar gravity, and is operationally straightforward, making it more suitable for in-situ lunar construction applications [13, 14]. Furthermore, DIW can be combined with subsequent sintering processes to tailor the properties of printed materials [15]. In this manufacturing route, DIW primarily defines the initial geometry and structural integrity of the printed green body, whereas subsequent sintering governs its densification behavior, the evolution of interparticle bonding, and ultimately its mechanical performance.

Sintering is a widely used consolidation process that has received increasing attention in the processing of lunar regolith materials. At elevated temperatures, sintering promotes particle diffusion, neck formation, and interparticle bonding, thereby facilitating densification and structural consolidation [16, 17]. The unique lunar environment is also highly relevant to the sintering process. In particular, the high-vacuum conditions on the lunar surface may induce the loss of volatile components and affect oxide films between particles, thereby exerting a complex influence on densification and microstructural evolution during sintering [18].

To better understand and optimize regolith sintering for 3D printing applications, a protective atmosphere such as argon can be introduced as a comparative processing condition for evaluating the influence of atmosphere on sintering behavior. Such a controlled atmosphere may also provide a useful reference for controlled processing environments that could be implemented in future lunar bases [19]. In addition to the atmosphere, sintering temperature plays a critical role in governing particle diffusion, neck growth, and pore evolution, which in turn affect the dimensional stability, microstructure, and mechanical performance of the resulting materials [20]. However, for 3D-printed lunar regolith structures, the effects of sintering atmosphere and temperature during post-processing on the final structural characteristics and mechanical performance remain insufficiently explored. In particular, the relationships among sintering conditions, densification behavior, microstructural evolution, and the resulting mechanical response of printed regolith components have not yet been systematically clarified. A better understanding of these relationships is therefore essential for optimizing post-printing thermal treatment and tailoring the final performance of additively manufactured lunar regolith structures.

In this study, we systematically investigate the microstructural evolution and mechanical performance of DIW-fabricated lunar regolith bricks subjected to different sintering atmospheres (vacuum and argon) and sintering temperatures ranging from 1050 to 1080 °C. By comparing shrinkage, mass loss, mechanical properties, and microstructural characteristics under these conditions, we examine the effects of sintering atmosphere and temperature on densification behavior, microstructural evolution, and mechanical response, and further discuss the possible relationships among densification, microstructural evolution, and mechanical response. The findings provide insights into the role of controlled sintering as a post-processing step for DIW-fabricated lunar regolith components and offer a basis for optimizing their performance for potential lunar construction applications.

2 Materials and Methods

2.1 Raw Materials

The lunar regolith simulant (LRS) used in this study belongs to the Jilin University (JLU) series and was prepared from volcanic ash collected in the Huinan region of Jilin Province, China. Its mineralogical composition is comparable to that of actual lunar regolith and consists primarily of feldspar and pyroxene, with minor olivine and volcanic glass. The major chemical constituents are presented in Figure 1 [21–23]. The particle size distribution was measured using a laser particle size analyzer (Bettersize2600), with particle sizes ranging from 1 μm to 1.28 mm, as shown in Figure 2b. Polylactic acid (PLA, 4032D) was used as the binder to consolidate the regolith simulant. PLA is an environmentally friendly and biodegradable polymer that can be dissolved in dichloromethane (DCM), a volatile solvent that evaporates during printing and subsequent curing.

2.2 Direct Ink Writing and Sintering

To ensure stable extrusion through the 410 μm nozzle, reduce the risk of clogging, and promote uniform filament formation and satisfactory surface quality, the LRS was sieved through a 75 μm mesh before slurry preparation. The binder system, consisting of 80 wt% DCM and 20 wt% PLA, was mixed with the sieved LRS using a planetary ball mill (XQM-2L) to obtain a homogeneous and printable slurry. The volume fractions of PLA and LRS in the solid constituents were 26% and 74%, respectively, with DCM serving as the solvent. The printing process was conducted using a 3D printer (AEP-2) under an extrusion pressure of 0.2–0.3 MPa and a printing speed of 15 mm/min. A grid

infill pattern with an infill percentage of 50% was adopted, and cubic green bodies with dimensions of $10 \times 10 \times 10$ mm were fabricated. The printed green bodies were then cured for 7 days to promote solvent evaporation and sufficient solidification of the PLA binder, thereby maintaining structural integrity before subsequent treatment and testing.

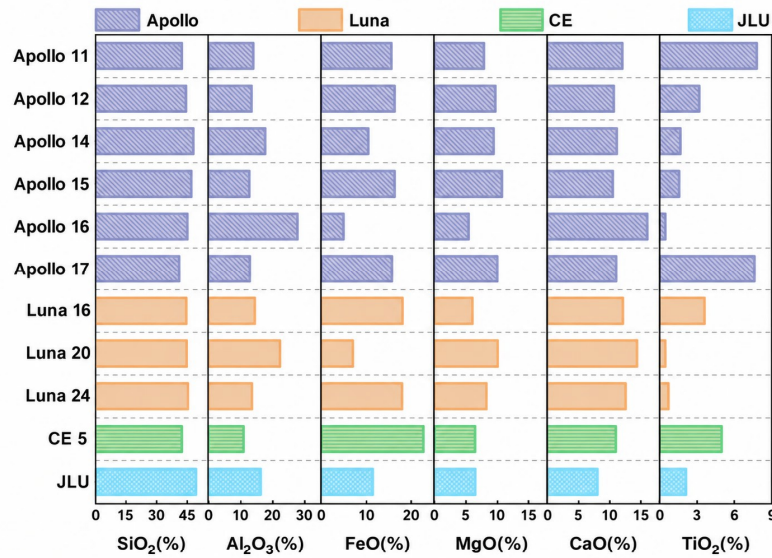


Figure 1. Major chemical constituents (wt%) of JLUR and lunar regolith samples from Apollo, Luna, and CE-5

Note: JLU = Jilin University; LRS = lunar regolith simulant; CE-5 = Chang'e-5. Apollo and Luna data are from the study [22], and CE-5 data are from the study [23].

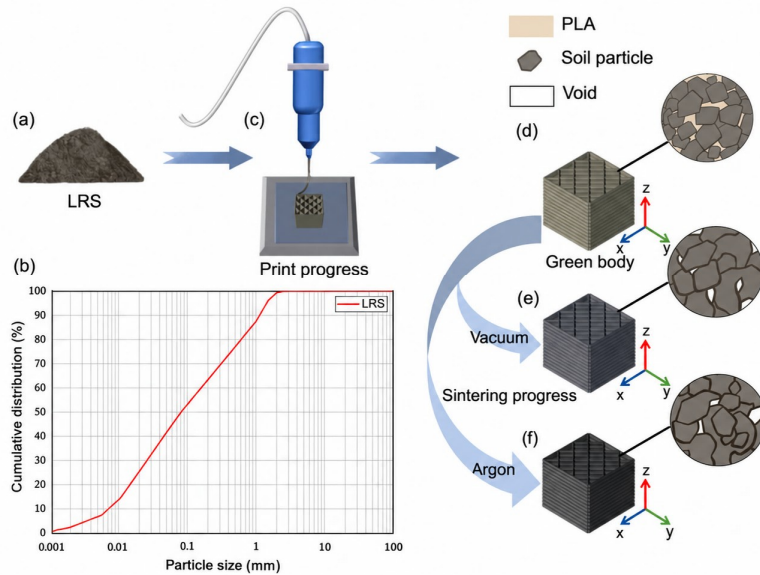


Figure 2. Schematic illustration of the 3D printing and sintering process: (a) LRS used for slurry preparation; (b) particle size distribution of the LRS; (c) DIW printing process at room temperature; (d) printed green body; (e) vacuum sintering; (f) argon sintering

Note: LRS = lunar regolith simulant; DIW = direct ink writing; PLA = polylactic acid; DCM = dichloromethane.

As illustrated in Figure 2, the prepared green bodies were subjected to two different sintering environments: vacuum and argon. The pressure values reported herein are gauge pressures referenced to atmospheric pressure. For the vacuum-sintered (VS) group, the furnace tube was evacuated using a vacuum pump until the gauge pressure, as

measured by the pressure gauge connected to the furnace tube, approached -0.1 MPa. For the argon-sintered (AS) group, high-purity argon gas was introduced into the furnace tube until the gauge pressure returned to approximately 0 MPa, corresponding to an internal pressure close to atmospheric pressure. The peak sintering temperatures for both the VS and AS groups were set at four levels: 1050, 1060, 1070, and 1080 °C. The four temperature conditions were denoted as VS1, VS2, VS3, and VS4 for vacuum sintering and AS1, AS2, AS3, and AS4 for argon sintering.

As shown in Figure 3, the sintering process for both the VS and AS groups consisted of three stages: heating, sintering (holding), and cooling. During the initial heating stage, the temperature was increased from room temperature to 400 °C and held for 30 min to facilitate binder removal from the specimens. The temperature was further increased to 800 °C and maintained for an additional 30 min. The heating rate was maintained at 10 °C/min up to 800 °C and was subsequently reduced to 5 °C/min until the designated peak sintering temperature was reached. During the sintering stage, the specimens were maintained at the target peak temperatures (1050–1080 °C) for 240 min under the corresponding sintering atmosphere. Finally, during the cooling stage, the specimens were cooled using the same rates as those applied during heating: first at 5 °C/min to 800 °C, followed by cooling from 800 °C to approximately 150 °C at 10 °C/min, after which the sintering treatment was considered complete.

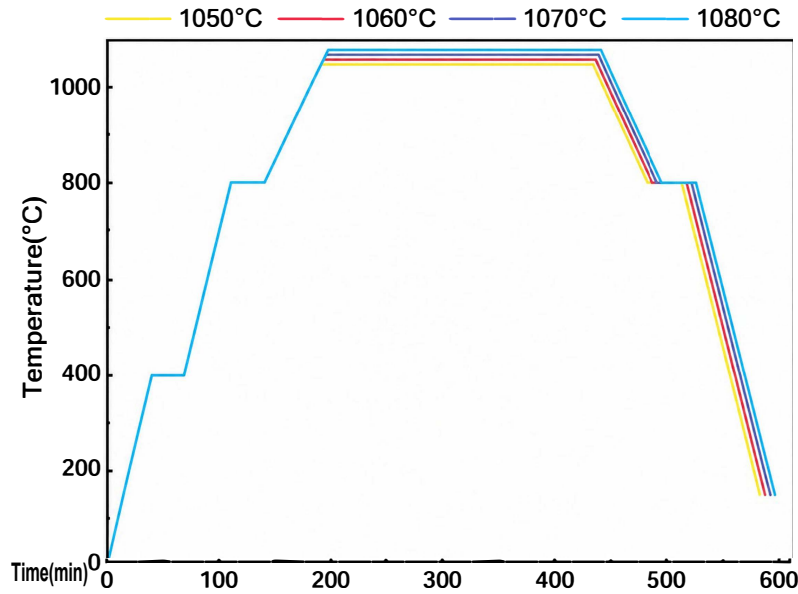


Figure 3. Sintering temperature profiles at different peak temperatures

2.3 Performance Testing

The dimensions and mass of each specimen were measured before and after sintering to determine the shrinkage and mass loss. For each experimental condition, three specimens were measured, and the results were reported as mean $\pm$ standard deviation (SD; $n = 3$). The same specimens were subsequently subjected to compressive strength testing using an electronic universal testing machine (WH-5000) at a loading rate of 1 mm/min. The force–displacement data recorded during testing were converted into stress–strain curves, from which the compressive strength of each specimen was determined. The compressive strength data were likewise reported as mean $\pm$ SD ($n = 3$).

For microstructural characterization, one additional specimen from each experimental condition was surface-polished and subsequently sputter-coated prior to examination by scanning electron microscopy (SEM, JSM-IT500).

3 Results and Discussion

3.1 Dimensional Variation

Variations in sintering atmosphere and temperature resulted in measurable differences in both the mass and dimensions of the specimens, as summarized in Table 1. Across all individual specimens, the mass loss ranged from 13.89% to 16.85%, whereas the corresponding group mean values reported in Table 1 ranged from 13.94% to 16.77%. The observed mass loss is primarily attributable to the thermal decomposition and removal of PLA during heat treatment. Binder removal may also generate additional pore space, allowing subsequent particle rearrangement during sintering, thereby promoting densification of the granular structure.

Considering the fine and slender geometry of the printed filaments and the 7-day curing period under ambient conditions prior to sintering, DCM was assumed to have completely evaporated before sintering for the purpose of

estimating the contribution of PLA to the mass loss. Under this assumption, the pre-sintering mass of the specimens was considered to consist of LRS particles and PLA. Based on the initial volume fractions of PLA and LRS in the solid constituents (26% and 74%, respectively), the mass fraction of PLA in the pre-sintering specimens was estimated from their respective densities as follows:

$$w_{\text{PLA}} = \frac{\phi_{\text{PLA}}\rho_{\text{PLA}}}{\phi_{\text{PLA}}\rho_{\text{PLA}} + (1 - \phi_{\text{PLA}})\rho_{\text{LRS}}} \quad (1)$$

where, ϕ_{PLA} is the initial volume fraction of PLA (26%), and ρ_{PLA} and ρ_{LRS} are the densities of PLA and LRS particles, respectively ($\rho_{\text{PLA}} = 1.26 \text{ g/cm}^3$, $\rho_{\text{LRS}} = 2.78 \text{ g/cm}^3$). DCM was not included in this calculation because it served as the solvent and was assumed to have evaporated during the curing period prior to sintering.

Table 1. Mass loss and dimensional shrinkage of sintered specimens

Temperature (°C)	Atmosphere	Mass Loss (%)	Dimensional Shrinkage (%)		
			<i>X</i>	<i>Y</i>	<i>Z</i>
1050	AS1	15.72 ± 0.13	1.80 ± 0.52	1.90 ± 0.17	1.64 ± 0.11
1050	VS1	13.94 ± 0.05	1.58 ± 0.56	2.43 ± 0.68	1.15 ± 0.19
1060	AS2	16.77 ± 0.08	2.38 ± 0.38	2.20 ± 0.28	1.79 ± 0.35
1060	VS2	14.36 ± 0.07	1.91 ± 0.86	2.06 ± 0.83	1.64 ± 0.36
1070	AS3	14.51 ± 0.05	3.53 ± 0.35	3.65 ± 0.27	4.17 ± 0.55
1070	VS3	14.20 ± 0.07	2.53 ± 0.28	2.23 ± 0.14	2.79 ± 0.09
1080	AS4	14.66 ± 0.14	7.39 ± 0.84	5.50 ± 1.35	6.10 ± 1.02
1080	VS4	14.85 ± 0.09	2.86 ± 1.16	4.40 ± 0.07	3.45 ± 0.99

Note: AS = argon-sintered; VS = vacuum-sintered.

The corresponding PLA mass fraction was calculated to be approximately 13.74%. Compared with the experimentally measured mass-loss range of 13.89%–16.85%, the excess mass loss beyond the estimated PLA contribution may be associated with the volatilization or thermal decomposition of minor volatile-bearing constituents in the LRS during high-temperature treatment. Therefore, the measured mass loss may reflect contributions from both PLA removal and additional thermally induced mass loss from the regolith simulant.

Notably, the group mean mass loss of the VS specimens showed an overall increasing tendency as the sintering temperature increased, rising from 13.94% at 1050 °C to 14.85% at 1080 °C, despite a slight decrease at 1070 °C. This variation suggests a relatively regular temperature-dependent pattern in the mass-loss behavior under vacuum. Higher peak temperatures may promote further removal or volatilization of thermally labile constituents, contributing to the overall increase in mass loss. In contrast, specimens sintered in an argon atmosphere exhibited a less regular variation in mass loss with temperature, with group mean values of 15.72%, 16.77%, 14.51%, and 14.66% at 1050, 1060, 1070, and 1080 °C, respectively. At 1050–1070 °C, the AS specimens exhibited both higher total mass loss and a greater excess beyond the estimated PLA contribution than the corresponding VS specimens, whereas at 1080 °C the VS specimens showed a slightly higher mass loss. These results suggest that the sintering atmosphere influences the additional mass-loss behavior of the LRS. Over most of the investigated temperature range, the argon condition was associated with greater additional mass loss, which may be related to atmosphere-dependent volatilization or thermal decomposition of minor volatile-bearing constituents in the LRS. Overall, the mass-loss behavior exhibited a relatively regular temperature-dependent tendency under vacuum, whereas greater fluctuations were observed under the argon condition.

Meanwhile, across all individual specimens, the directional shrinkage ranged from 0.96% to 8.23%, whereas the group mean directional shrinkage values reported in Table 1 ranged from 1.15% to 7.39%. The shrinkage exhibited clear directional dependence between the in-plane directions (*X* and *Y*) and the direction perpendicular to the printing plane (*Z*). For specimens sintered under different atmospheres, shrinkage generally increased with increasing temperature. This trend may be associated with enhanced particle rearrangement and densification at elevated temperatures. The shrinkage in the *Z* direction increased markedly at 1070 and 1080 °C. At 1070 °C, the mean shrinkage in the *Z* direction was greater than that in the *X* and *Y* directions under both atmospheres. At 1080 °C, however, the largest mean shrinkage occurred in the *X* direction for the AS specimens and in the *Y* direction for the VS specimens. These results indicate that the anisotropic contraction evolved with increasing temperature rather than remaining dominated by a single direction. The greater dimensional contraction at elevated temperatures may be associated with enhanced particle rearrangement, mass transport, and densification during sintering. Under identical temperature conditions, specimens sintered in an argon atmosphere generally exhibited greater shrinkage than those sintered in vacuum, particularly at higher temperatures. At 1070 and 1080 °C, the mean shrinkage values in all three directions were higher for the AS specimens than for the corresponding VS specimens.

At 1080 °C, the maximum mean directional shrinkage reached 7.39% for the AS specimens, compared with 4.40% for the VS specimens. Overall, the results demonstrate that both sintering temperature and atmosphere influence the dimensional contraction of the printed specimens, with the effect of increasing temperature being more pronounced under the argon condition.

3.2 Compressive Strength

Figure 4a–Figure 4c present the stress–strain curves of the LRS unsintered specimen (NS) and the specimens sintered at different peak temperatures under vacuum and argon atmospheres. All curves start near zero stress and initially increase with increasing strain. At the initial stage of deformation (approximately 0–2% strain), a distinct compaction stage is observed, which may be primarily associated with the closure of interlayer gaps and intrinsic pores within the printed filaments. This is followed by a linear elastic region, where stress increases proportionally with strain. With further loading, the curves transition into a nonlinear deformation stage prior to reaching the peak stress. Beyond the peak, a pronounced stress drop occurs, indicating the onset of material failure and structural degradation. The NS specimen shown in Figure 4a displays a relatively smooth stress–strain response, indicating a comparatively uniform and stable deformation process. In contrast, regardless of the sintering atmosphere, the sintered specimens exhibit distinctly different mechanical behavior compared with the unsintered material, with the deformation response shifting from plastic-like behavior toward a quasi-brittle response. Beyond the linear elastic regime, the stress–strain curves become distinctly irregular and serrated, with fluctuations becoming increasingly pronounced during the failure stage. These fluctuations may reflect the progressive initiation and propagation of microcracks and local structural damage, accompanied by redistribution of internal load-bearing paths. Together, these observations indicate that the sintering process markedly alters the deformation and failure behavior of the material.

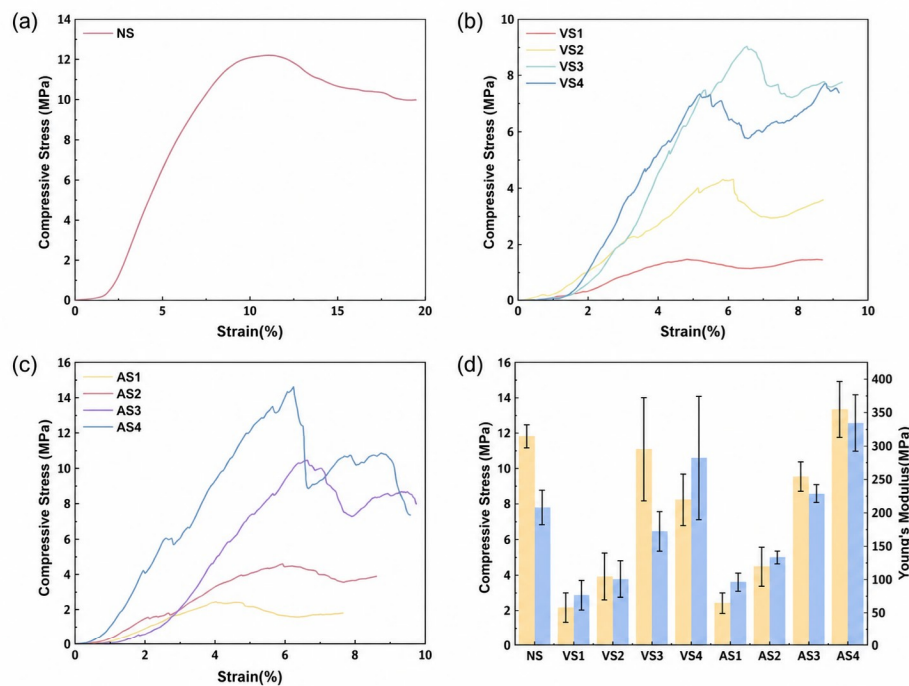


Figure 4. Compressive stress–strain curves of the (a) NS, (b) VS, and (c) AS specimens, together with (d) compressive strength and Young's modulus

Note: NS = unsintered specimen; VS = vacuum-sintered; AS = argon-sintered; Error bars represent the standard deviation of three measurements.

The corresponding compressive strength and Young's modulus under the nine processing conditions are summarized in Figure 4d. Compared with the specimens sintered at 1050–1060 °C, the NS exhibits both higher peak stress and greater deformation capacity, which can be attributed to the presence of the binder that provides effective interparticle adhesion and enables improved stress redistribution during compression. The NS specimen exhibits a compressive strength of 11.84 ± 0.64 MPa and a Young's modulus of 208.33 ± 25.81 MPa. For sintered specimens, particularly at relatively low sintering temperatures (1050–1060 °C), the compressive strength is generally lower than that of the NS specimen. This reduction may be associated with binder removal during sintering before sufficient interparticle bonding and densification have developed. At this stage, sintering-induced

densification appears insufficient to compensate for the structural deficiencies arising from binder removal, resulting in reduced load-bearing capacity and a more brittle mechanical response. With increasing sintering temperature, the mechanical properties generally improve, although the evolution of compressive strength differs between the two sintering atmospheres. The compressive strength of the AS series increases progressively from 2.43 ± 0.58 MPa at $1050\text{ }^{\circ}\text{C}$ to 13.35 ± 1.58 MPa at $1080\text{ }^{\circ}\text{C}$, whereas that of the VS series increases from 2.18 ± 0.84 MPa at $1050\text{ }^{\circ}\text{C}$ to a maximum of 11.11 ± 2.91 MPa at $1070\text{ }^{\circ}\text{C}$ and then decreases to 8.27 ± 1.44 MPa at $1080\text{ }^{\circ}\text{C}$. Among the sintered specimens, VS3 exhibits a compressive strength close to that of the NS specimen, whereas AS4 exceeds the NS value and exhibits the highest compressive strength. In particular, AS4 reaches a compressive strength of 13.35 ± 1.58 MPa, representing an increase of approximately 12.75% relative to the NS specimen. Its Young's modulus reaches 334.43 ± 42.32 MPa, corresponding to an increase of approximately 60.53% relative to the NS specimen. This pronounced increase in stiffness indicates enhanced structural rigidity after sintering. Thus, under the AS4 condition, both compressive strength and stiffness exceed those of the NS.

A clear distinction is also observed between different sintering atmospheres. The AS series exhibits a higher Young's modulus than the corresponding VS series at all investigated temperatures. For compressive strength, the AS specimens exhibit higher mean values than the corresponding VS specimens at 1050 , 1060 , and $1080\text{ }^{\circ}\text{C}$, whereas VS3 shows a higher mean strength than AS3 at $1070\text{ }^{\circ}\text{C}$. This difference may be associated with variations in microstructural evolution during sintering. Overall, the mechanical performance of the specimens exhibits distinct responses to sintering atmosphere and temperature. The consistently higher Young's modulus of the AS specimens, together with the highest compressive strength observed for AS4, is consistent with atmosphere-dependent differences in structural consolidation during sintering. These differences in mechanical behavior may be related to the evolution of the internal microstructure during sintering, as further examined through microstructural observations in Section 3.3.

3.3 Microstructural Analysis

As illustrated in Figure 5, the microstructure of the green body (NS specimen) at $300\times$ magnification shows that the LRS particles are primarily bonded through the solidified PLA distributed over their surfaces. In this case, the overall strength of the NS arises from the combined effect of the PLA binder and LRS particles. Specifically, PLA promotes interparticle bonding and enhances structural integrity by bridging adjacent particles and reducing the influence of local structural heterogeneities. As a result, the specimen exhibits more uniform deformation and a relatively smooth, plastic-like stress–strain response.

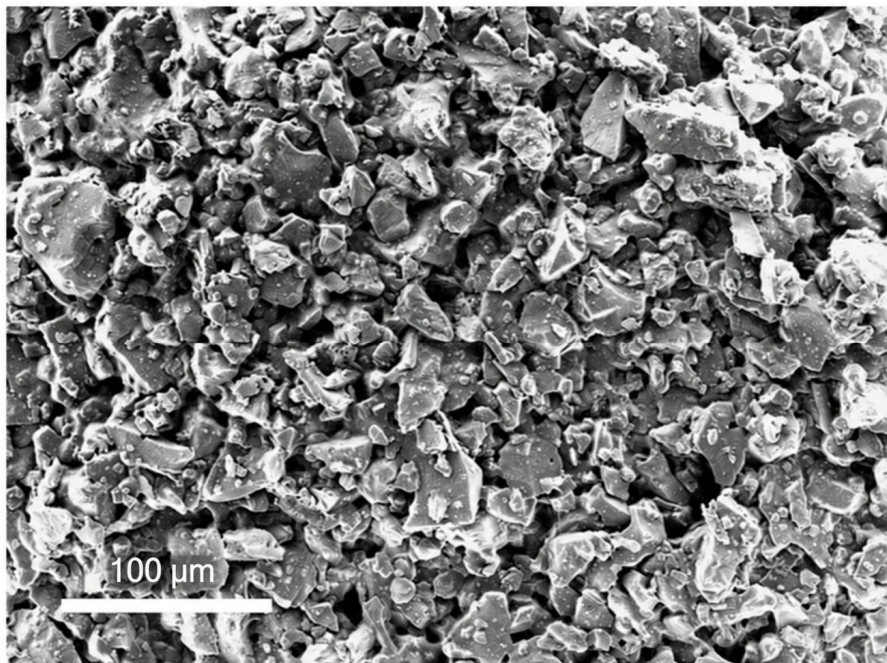


Figure 5. SEM micrograph of the unsintered green body (NS specimen)

Note: SEM = scanning electron microscopy; NS = unsintered specimen.

However, as illustrated in Figure 6, discernible structural voids are observed in the VS1, VS2, AS1, and AS2 groups, indicating incomplete sintering at relatively low peak temperatures. Following PLA pyrolysis, the release of gaseous products may leave voids in regions previously occupied by the binder, while the sintering temperatures

appear insufficient to promote effective particle bonding and the formation of adequate sintering necks to compensate for these pores. As a result, a relatively porous structure is retained, leading to inferior mechanical properties compared with the NS specimen, which is consistent with the low compressive strengths shown in Figure 4d. At these lower temperatures, although the VS specimens exhibit fewer visible voids, the pores are more heterogeneously distributed and the overall structure appears relatively loose, which may promote local stress concentration and contribute to their lower compressive strengths than those of the corresponding AS specimens.

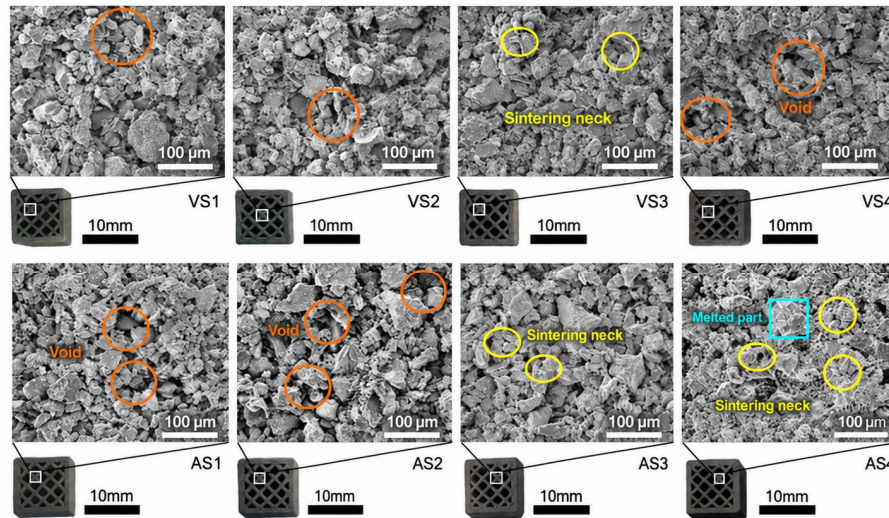


Figure 6. Optical and SEM images of specimens sintered under vacuum and argon atmospheres at different temperatures

Note: SEM = scanning electron microscopy; VS = vacuum-sintered; AS = argon-sintered.

At 1070 °C, both the VS and AS groups show partial sintering of regolith particles, with the formation of noticeable sintering necks. The resulting interparticle bonding is more extensive than that observed at 1050–1060 °C, which is consistent with the marked increase in compressive strength at 1070 °C reported in Section 3.2. As the temperature further increases, distinct differences between the two atmospheres become more evident. In the VS group, although some sintering necks are present at 1080 °C, larger voids are again observed, and the microstructure becomes more heterogeneous. These features may interrupt continuous load-bearing paths and provide a possible microstructural explanation for the decrease in compressive strength from VS3 to VS4, as observed in Section 3.2. Compared with AS3, AS4 exhibits better-developed sintering necks, more continuous interparticle bonding, and partial coalescence of locally molten regions, forming locally fused bulk structures and a more consolidated microstructure, which is consistent with its highest compressive strength and Young's modulus among the sintered specimens.

The sintering behavior is consistent with a liquid-phase-assisted mechanism. Once the temperature is sufficiently high, partial melting of certain components may form a small amount of liquid phase, transforming some interparticle contacts from solid–solid to solid–liquid–solid configurations. Under these conditions, mass transport may be enhanced, promoting the progressive formation and growth of sintering necks between particles, while the original pores may be gradually reduced, thereby contributing to overall densification.

At relatively low temperatures (1050–1060 °C), liquid-phase formation appears to be limited, which may result in slower neck growth, incomplete pore closure, and limited bulk densification. As a result, dimensional shrinkage remains relatively small. As the temperature increases (1070–1080 °C), greater liquid-phase formation may occur and enhance particle migration and rearrangement, thereby promoting pore reduction and overall densification. Accordingly, dimensional shrinkage becomes more pronounced at higher temperatures, consistent with the overall increase in shrinkage at higher temperatures observed in Section 3.1. Therefore, the pronounced differences observed among specimens sintered at different temperatures may be associated with the temperature-dependent formation of the liquid phase and its influence on mass transport, interparticle bonding, and the overall densification process.

The difference between the AS and VS groups may be associated with the combined effects of PLA pyrolysis and the sintering atmosphere. During PLA pyrolysis, the release of gases (e.g., carbon dioxide) may generate internal porosity [24]. Under vacuum conditions, the low-pressure environment may affect pore evolution and local transport processes during sintering, thereby influencing neck formation and densification. As the temperature increases, partial densification may occur; however, the low external gas pressure may be insufficient to fully counteract the expansion of residual gases trapped within closed pores. In addition, pore coarsening may occur at elevated

temperatures, resulting in the growth and coalescence of pores. Under these conditions, material transport may not keep pace with pore growth sufficiently to achieve complete neck development and pore closure. Consequently, the liquid phase may not fully compensate for the enlarged voids, allowing residual pores to persist or coalesce and thereby limiting overall densification.

In contrast, the presence of argon provides a gaseous medium within the pore space, which may alter heat transfer and local mass transport conditions during sintering and thereby favor more uniform interparticle bonding. The external gas environment may also help limit excessive pore expansion and maintain interparticle contact, facilitating neck growth and densification. The more consolidated microstructure observed in AS4 is consistent with its highest compressive strength and Young's modulus among the sintered specimens. This microstructural evolution is also consistent with the greater dimensional shrinkage observed under argon than under vacuum at 1070 and 1080 °C, as discussed in Section 3.1. Based on the above analysis, the key difference between vacuum and argon atmospheres may lie in their different influences on pore evolution and local transport conditions, which could affect the competition between densification and pore growth during sintering.

4 Conclusion

This study employed DIW to fabricate LRS composites and systematically examined the effects of post-printing sintering temperature and atmosphere (vacuum and argon) on dimensional shrinkage and mechanical performance, with microstructural analysis providing insights into the associated structural evolution.

The results show that increasing sintering temperature generally promoted dimensional contraction and structural consolidation, although the mechanical response depended on the sintering atmosphere. The compressive strength of the AS specimens increased continuously from 1050 to 1080 °C, whereas that of the VS specimens increased up to 1070 °C and then decreased at 1080 °C. The observed microstructural evolution is consistent with a liquid-phase-assisted sintering mechanism. At higher temperatures, increased liquid-phase formation may promote particle rearrangement, interparticle bonding, and pore reduction, thereby contributing to enhanced densification and mechanical performance. Sintering atmosphere also played an important role in pore evolution and the resulting mechanical behavior. Under vacuum, the low-pressure environment may influence local transport and pore evolution during sintering, while pore growth and coalescence at elevated temperatures may compete with densification, as reflected by the heterogeneous microstructure and reduced compressive strength of VS4. In contrast, the presence of argon may provide more favorable conditions for maintaining interparticle contact and promoting the development of sintering necks, resulting in a more consolidated microstructure at higher temperatures. At 1070 and 1080 °C, the mean shrinkage values in all three directions were greater under argon than under vacuum. Among all investigated conditions, the specimen sintered at 1080 °C under an argon atmosphere exhibited the maximum mean directional shrinkage of 7.39%, the highest compressive strength of 13.35 ± 1.58 MPa, and the highest Young's modulus of 334.43 ± 42.32 MPa among all specimens, indicating the most favorable overall performance within the investigated processing window.

Collectively, the combined effects of sintering temperature and atmosphere influence the competition between densification and pore evolution, thereby affecting the final mechanical performance of DIW-fabricated LRS composites. Within the investigated processing window, high-temperature sintering under an argon atmosphere provided the most favorable overall conditions for enhanced densification and mechanical performance. The results further demonstrate the importance of coordinating DIW shaping with subsequent thermal processing to achieve effective particle bonding and structural consolidation. These findings offer valuable insights into the optimization of post-processing parameters for additively manufactured regolith-based structures and contribute to the development of high-performance structural materials for potential lunar construction applications.

The present findings were obtained using the JLU LRS under vacuum and argon sintering conditions, and therefore primarily reflect the sintering behavior of this specific material system within the investigated processing window. Whether similar trends can be extended to other LRSs or different sintering conditions warrants further investigation. In addition, the applicability of the DIW-based fabrication process under lunar surface conditions will be further investigated in future work.

Author Contributions

Conceptualization, Y.Y.C. and A.L.X.; methodology, Y.Y.C. and A.L.X.; formal analysis, Y.Y.C.; investigation, Y.Y.C. and A.L.X.; data curation, Y.Y.C.; review of literature, Y.Y.C. and A.L.X.; visualization, Y.Y.C. and A.L.X.; writing—original draft preparation, Y.Y.C. and A.L.X.; writing—review and editing, Y.Y.C. and L.Z.; supervision, L.Z.; resources, L.Z. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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