Fused Filament Fabrication on the Moon

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Additive manufacturing techniques have the capability to produce complex and customized parts rapidly, typically in low volume and with reduced material usage. These attributes magnify their indispensability when the availability of materials and equipment is limited, as may be the case in future manned lunar explorations. This article presents a preliminary discussion on the possibility of performing fused filament fabrication (FFF) on the Moon from the perspective of heat transfer in printed parts. It makes use of experimental data and simulations at different print resolutions to quantify the significance of each heat transfer mechanism taking place during printing. The quantification then enables us to investigate how the lunar environment affects the cooling of printed parts. Finally, FFF on the Moon is predicted to be feasible. However, apparent differences in the process window and types of applications are pointed out, as compared with counterpart printing activities on Earth.

List of symbols

Bi	Biot number, $Bi = h\hbar/\lambda$
c_p	Isobaric specific heat capacity (J/g/K)
h	Convective heat transfer coefficient (W/m ² /K)
$\hbar (= \delta z)$	Layer thickness/height (mm)
q	Heat flux intensity (W/m ²)
t	Time (s)
t_0	Location-specific deposition moment (s)
t_x	An unknown time (s)
T	Temperature, $T = T(r, t) = T(x, y, z, t)$ (°C, K)
T_a	Air temperature above the build plate (°C, K)
T_n	(nominal) Nozzle temperature (°C, K)
T_p	Plate temperature (°C, K)
T_x	An unknown temperature (°C, K)
T_∞	Room (far environment) temperature (°C, K)
v	(relative) Nozzle travel speed (mm/s)
δt	Time step (s)
δU	Total energy loss (J)
δU_{cond}	Energy loss by conduction (J)
δU_{conv}	Energy loss by convection (J)
δU_{rad}	Energy loss by thermal radiation (J)

$(\delta x, \delta y, \delta z)$	Element dimensions (mm)
$\Delta \tau$	Interlayer time (s)
ε	Material emissivity (100%)
λ	Thermal conductivity (W/m/K)
ρ	Mass density (g/cm ³)

INTRODUCTION

Future manned lunar operations would require a base to be built for long-term human activities. The operation and maintenance of such a Moon base need different manufacturing techniques to support long-duration and long-endurance activities. In particular, additive manufacturing (AM) techniques could play a vital role, as they have the capability to produce low volume and highly customized parts rapidly with reduced material usage and preparation tools. These attributes magnify their indispensability when traditional manufacturing techniques and materials are limited or not immediately available on the Moon. Fused filament fabrication (FFF), one of the material extrusion-based AM techniques, is even more promising for long-duration missions as the thermoplastic materials used can be

recycled,^{1,2} which further reduces the material consumption and logistic cost, hence promoting the self-sustainability of the process. However, can FFF succeed on the Moon in the first place?

Herein, FFF on the Moon refers to an FFF process to be performed on the lunar surface outside a pressurized room/chamber. This specification of the environment is necessary since the thermal process involved will inevitably emit volatile organic compounds and ultrafine particles.^{3–5} If released in a sealed environment, these chemical compounds would raise concerns over crew health. Unless an effective ventilation system were installed, this would limit use to only limited verified materials. On the other hand, FFF on the Moon but in a pressurized room/chamber is less challenging, as the only difference from the counterpart printing on Earth is the gravity intensity. Nevertheless, gravity is noncritical for FFF.

In a two-phase in-space manufacturing project in 2014 and 2016, the National Aeronautics and Space Administration (NASA) demonstrated that the 0 G environment in the International Space Station (ISS) did not fundamentally affect FFF.^{6,7} This demonstration project clearly showed that microgravity does not have a significant effect on the morphology and properties of printed parts from an engineering standpoint, and that FFF can succeed in a 0G environment. The rationale is that the ratio between a body force (weight) and a surface/line force (polymer melt surface tension) decreases with an object's dimension. The typical layer thickness in FFF is in the range of 100 μm to 300 μm , far below the typical capillary length of polymer melts (with a magnitude of 1 mm⁸). Hence, gravitational forces can be neglected.⁹ As circumstantial evidence, Zawaski and Williams successfully printed in an upside-down way at a layer thickness of 200 μm on Earth,¹⁰ suggesting that changing the direction of gravity is nondetrimental to FFF; besides, gravitation was never found influential in liquefier kinetics, polymer melt spreading, bond formation, or heat transfers or stress development after printing.^{11–13} On the lunar surface, the gravity intensity is $\sim 1/6$ of that at the Earth's surface (1.62 versus 9.80 m/s^2). However, this reduced gravity environment can reasonably be assumed to be noncritical for FFF.

On the other hand, the ultrahigh-vacuum environment on the Moon brings real challenges.

The pressure on the lunar surface is on the magnitude of 3×10^{-10} Pa.¹⁴ Thermal convection thus almost completely disappears due to a lack of energy carriers to realize heat diffusion and advection (3×10^4 molecules/ cm^3 at 10^{-10} Pa versus 2×10^{19} molecules/ cm^3 at 1 atm.¹⁵). Indeed, a reduction in the environmental pressure p from 10^5 Pa to 10^3 Pa will lead to a reduction in the convection coefficient from 10^1 $\text{W/m}^2/\text{K}$ to 10^0 $\text{W/m}^2/\text{K}$.¹⁶ Such a pressure change by two orders of magnitude already shows a noticeable influence. As reported by

Quinn et al.,¹⁷ FFF could work properly in a reduced vacuum environment at $p = 10^3$ Pa, an environment temperature of 25°C, and 1 G. The printed parts showed generally improved mechanical properties compared with counterparts printed in the normal environment ($p = 10^5$ Pa), benefiting from reduced cooling due to the diminished convection in the vacuum. However, the leading author also reported printing failures because of the slow cooling in the same vacuum, whereas printing was successful in the normal environment (fig. 31 versus fig. 30 in Ref. 18). Such printing failures strongly suggest that FFF on the Moon could be even more challenging with respect to thermal management.

Apart from the diminished natural convection in printed parts, all gaseous convection-related mechanics in FFF machines will cease to work on the Moon: the heat sink and the part cooling fan working on forced convection will no longer be functional. The heat sink dysfunction is detrimental as it can lead to filament heating above the heat-break and stop smooth filament feeding. In addition, the heating control of the hot-end and build plate might need adjustments, and the stepper motors may also require additional cooling to ensure their performance during the printing. A specifically engineered FFF machine in the future could possibly overcome these obstacles for lunar applications. However, the challenges of thermal management in printed parts still exist.

This article presents a preliminary analysis of the possibility of applying FFF on the Moon from the perspective of heat transfers in printed parts. First, the fundamental heat transfer mechanisms in printed parts are investigated and quantified when printing at different resolutions (where high resolution means low layer thickness). It is demonstrated how the lunar environment would affect the temperature variations during printing. This possibility is thus evaluated, along with predictions on the efficiency and process window of FFF on the Moon.

MATERIALS AND METHODS

Temperature in printed parts from three sets of experimental work on Earth was reproduced from Refs. 19–21 for comparison and analysis. The experimental and simulation details can be found therein. Table I summarizes relevant technical details. In particular, the experimental data in dataset 2 were kindly shared by Arthur Lepoivre from the Université de Nantes;²⁰ experimental data in dataset 3 were kindly shared by Brett G. Compton from the University of Tennessee.²¹ Permissions for reproduction were obtained from Elsevier. These datasets represent FFF at different resolutions on Earth, each exhibiting unique patterns during cooling.

FFF was then analyzed to evaluate the contribution of each heat transfer mechanism during the cooling of parts printed at different resolutions. High-resolution printing on the Moon was selected

Table I. Details of representative FFF processes at different printing resolutions

	Dataset 1 ¹⁹	Dataset 2 ²⁰	Dataset 3 ²¹
Resolution	High	Medium	Low
Layer thickness, $\bar{h}$ ($= \delta z$) (μm)	300 ^a	800	4064
Material	PLA	ABS	CF/ABS
Technology	FFF	FFF	BAAM ^b
Geometry	Double-wall	Single-wall	Single-wall
Dimensions, $L \times W \times H$ (mm)	$18 \times 0.8 \times 12$	$60 \times 1.25 \times 50$	$1542 \times 20 \times 358$
Strand width, $\xi\phi(\sim \delta y)$ (μm)	400	1250	20,000
Δx (μm)	439	1463	37,610
Travel speed, v (mm/s)	5	6.741	39.54
Nozzle temperature, T_n ($^{\circ}\text{C}$)	203	255	200
Plate temperature, T_p ($^{\circ}\text{C}$)	57.1	100	65
Room temperature, T_{∞} ($^{\circ}\text{C}$)	21.2	95	18
Air temperature, $T_a(z)$ ($^{\circ}\text{C}$)	$35.9 \text{ e}^{\frac{-z [\text{mm}]}{9.443}} + 21.2$	95	$47 \text{ e}^{\frac{-z [\text{mm}]}{9.443}} + 18$
Density, ρ (g/cm^3)	$\rho = \rho(T)$ ²²	1.05	1.14
Specific heat capacity, c_p ($\text{J}/\text{g}/\text{K}$)	$c_p = c_p(T)$ ²³	2.1	1.64
Thermal conductivity, λ ($\text{W}/\text{m}/\text{K}$)	0.195	0.2	0.17
Convection coefficient, h ($\text{W}/\text{m}^2/\text{K}$)	60	8.5	8.5
Emissivity, ε	0.78	0.91	0.87
Location of interest	(9,0,6) (mm)	6th layer	45th layer
Interlayer time, $\Delta\tau$ (s)	7.2	8.9	39
Maximum cooling rate ^c ($^{\circ}\text{C}/\text{s}$)	246 (306)	65 (36)	0.9 (1.7)
Volume flow rate (cm^3/h)	2.2	24	1.2×10^4
Biot number, Bi^d	0.013 (0.092)	0.034 (0.24)	0.21 (1.4)

^a300 μm is rather “coarse” even for desktop machines, but is considered high resolution in FFF in general.

^bBig Area Additive Manufacturing. Strictly, BAAM is not an FFF technique, but the thermal process after the polymer melt leaves the nozzle resembles that in FFF.

^cThe cooling rate here refers to its intensity, i.e., $|\partial T/\partial t|$. The first number was calculated with experimental data, and the second one in parentheses with simulations. The calculation employed a central difference scheme.

^d $\text{Bi} = h\bar{h}/\lambda$. The first number was calculated based on natural convection, taking $h = 8.5 \text{ W}/\text{m}^2/\text{K}$; the second one in parentheses was based on forced convection, taking $h = 60 \text{ W}/\text{m}^2/\text{K}$.

for further analyses, based on an extension from forced, to natural, to zero convection, with additional consideration of the lunar ambient environment temperature $T_{\infty} = -20^{\circ}\text{C}$.¹⁴

Reproducible simulations were performed based on the validated T4F³ model openly available from the Advanced Manufacturing Lab, KU Leuven.¹⁹ In the simulations, the dependence of the mass density on pressure is neglected, with $\partial\rho/\partial p$ estimated to be on the order of $3 \times 10^{-4} \text{ g}/\text{cm}^3/\text{MPa}$ based on the p - V - T data in Ref. 22. The pressure dependence of the heat capacity c_p and thermal conductivity λ is unknown. But it is assumed to be indiscernible, as a pressure change by 0.1 MPa is rather limited for condensed materials. Generally, the uncertainties in these material properties are significantly lower than those in bond length/width, convection uniformity, conduction anisotropy, etc.^{19,24,25} Hence, the same material properties as used in FFF simulations on Earth are applied in the simulations on the Moon. The possibility of FFF on the Moon is evaluated mainly based on the temperature fields and their variations.

RESULTS AND DISCUSSION

Printing at Different Resolutions

The resolution in FFF commonly refers to the layer thickness, which is a measure of the most delicate structure possible with the AM technique. The lower limit of layer thickness is usually determined by the accuracy of the motion system, while the upper limit is determined by the nozzle design and diameter. Thus, current understanding of the role of the layer thickness is practically limited to a narrow range that is hardware specific. For example, with an E3D nozzle of 400 μm diameter, the applicable layer thickness typically ranges between 50 μm and 400 μm . To probe how the layer thickness impacts FFF in general, different datasets from printing with a wider range of resolutions are needed.

Figure 1a presents such temporal temperature profiles from three datasets obtained at different resolutions. Each contains both experimental monitoring and simulations (denoted by “Exp.X” with dotted lines and “Sim.X” with solid lines,

Fig. 1. (a) Temporal temperature profiles in FFF at different resolutions. The profiles come from three datasets with layer thickness of $h = 300 \mu\text{m}$ (Exp.1, Sim.1-1 [forced convection] and Sim.1-2 [natural convection]), $800 \mu\text{m}$ (Exp.2 and Sim.2), and $4064 \mu\text{m}$ (Exp.3 and Sim.3). Dotted lines indicate experimental data; solid lines are simulations. Figure reproduced from Refs. 20, 21 with permission from Elsevier. (b) Demonstration of element dimensions ($\delta x, \delta y, \delta z$) and the intralayer and interlayer reheatings in an FFF-printed double-wall structure.

respectively). The normalized temperature is given by $(T - T_\infty)/(\max T - T_\infty)$, where T_∞ is the room temperature.

When the resolution is high, e.g., at layer thickness $h = 300 \mu\text{m}$, the printed part experiences rapid cooling upon deposition (Fig. 1a). The maximum transient cooling rate is on the order of $10^2 \text{ }^\circ\text{C/s}$ (Table I). The cooling is due to the combined effects of thermal conduction with the neighboring element below (and in the same layer if applicable), forced thermal convection with the local air above the build plate, and thermal radiation with the far environment. Soon after deposition, the temperature in a local strand segment drops to a level close to room temperature in seconds, then reheatings take place due to thermal contacts with the neighbors in the same layer (intra-layer reheating, Fig. 1b) or the layer above (inter-layer reheating). Small peaks appear accordingly at each reheating moment. The reheatings can penetrate through multiple layers (secondary reheatings) when the layer thickness is low. Switching off the part cooling fan will not fundamentally change these cooling/reheating characteristics: As shown by Sim.1-2 for the natural convection scenario, the maximum transient cooling rate is of the same magnitude as the forced convection case ($-232 \text{ }^\circ\text{C/s}$, Table I), and the reheating peaks can penetrate as many layers. This is because thermal conduction plays a critical role in the part cooling. The conductive heat flux is inversely proportional to the layer thickness h :

$$|q_{\text{cond}}| = |-\lambda \nabla T| \approx \lambda \Delta T / h \propto 1/h, \quad (1)$$

where ΔT is the temperature difference between two layers and λ is the material thermal conductivity. As long as the layer thickness is small, the energy lost by conduction will be significant, and the heat will penetrate through considerable layers. For even thinner layers in FFF (e.g., $< 100 \mu\text{m}$), thermal conduction will dominate the cooling, regardless of the convection intensity.

On the other hand, when the resolution is low, e.g., at a layer thickness $h = 4064 \mu\text{m}$ in dataset 3, the cooling profiles show different patterns. The overall cooling is significantly slower. It takes minutes for the printed part to show a noticeable decrease in temperature, and hours to cool down completely. The maximum transient cooling rate is around $10^0 \text{ }^\circ\text{C/s}$, two orders of magnitude slower than in the high-resolution case (Fig. 1a; Table I). In addition, the reheating peaks are no longer apparent. Their disappearance indicates a lower importance of heat conduction. For an intermediate resolution, e.g., the layer thickness of $h = 800 \mu\text{m}$ in dataset 2, the cooling characteristics lie between these two extremes: the overall cooling is moderate, with a maximum cooling rate on the order of $10^1 \text{ }^\circ\text{C/s}$, and the reheating due to thermal conduction is apparent but can only penetrate through limited layers.

These differences in the temperature profiles can be explained based on the Biot number, which quantifies the relative significance of heat transfer by convection (outside the strand) versus conduction (within the strand). $Bi = h\bar{h}/\lambda$, where h and λ are the convection coefficient and conductivity, respectively, and $\bar{h}$ is the layer thickness. Since $\bar{h}$ can vary by two orders of magnitude in FFF (e.g., from $50 \mu\text{m}$ to $5000 \mu\text{m}$), Bi can vary as widely. From Table I, $Bi < 0.1$ is typical for a layer thickness of $300 \mu\text{m}$, even with forced convection, indicating that thermal conduction prevails during the process. The deposited material cools/reheats quickly due to thermal contact with the cooler or newly deposited hotter neighbor(s), and the temperature field within the strand element is uniform. This fast cooling in high-resolution printing explains why amorphous microstructures are typical in printed parts even with semicrystalline polymers.²⁶ On the contrary, thermal convection, along with thermal radiation, plays an indispensable role in the energy transfer

when the layer thickness is medium or high, and Bi can reach 0.2 even for natural convection in high-flow-rate printing (Table I). As such, the heat transfer problem is thermally complex within the strand, and the gravity could be problematic in printing large structural components.

Moreover, Fig. 1a also points out two future directions for FFF (summarized in Table II): one focuses on higher-resolution printing, more suited for precision manufacturing of functional components, where thermal conduction dominates the cooling; the other focuses on high volume flow rates to print large or structural components, when production efficiency is more of a concern, and thermal convection and radiation play the crucial role during cooling.

However, how can one quantify the dominance of thermal conduction, convection, or radiation during the process? In other words, what are the exact contributions from each heat transfer mechanism during the cooling?

Significance of Each Heat Transfer Mechanism

The heat transfer process in printing the double wall in dataset 1 is shown schematically in Fig. 2a, where an element segment J21 before its intralayer reheating is taken for analyses. Its temporal temperature profiles are shown in Fig. 2b, along with the temperature of the adjacent element J20 in the previous layer.

From the deposition moment at t_0 to any later time t_x , element J21 cools from the nominal nozzle temperature T_n to some lower temperature T_x (to be determined). During this process, its total energy loss δU can be decomposed into the energy loss by conduction δU_{cond} , convection δU_{conv} , and radiation δU_{rad} , i.e.,

$$\delta U = \delta U_{cond} + \delta U_{conv} + \delta U_{rad}. \quad (2)$$

The significance of each heat transfer mechanism during the cooling is defined as the contribution of each mechanism to the total energy loss: $\delta U_{cond}/\delta U$, $\delta U_{conv}/\delta U$, and $\delta U_{rad}/\delta U$. Apparently, these contributions add up to unity for any selected time period, manifesting the principle of energy conservation (ignoring melt crystallization for semicrystalline polymers)

$$\frac{\delta U_{cond}}{\delta U} + \frac{\delta U_{conv}}{\delta U} + \frac{\delta U_{rad}}{\delta U} = 1. \quad (3)$$

On the other hand, δU can be physically determined by the difference in the internal energy U

$$\begin{aligned} \delta U &= U(T_x) - U(T_n) = \int_{T_n(t_0)}^{T_x(t_x)} mc_p dT \\ &= \delta x \delta y \delta z \int_{T_n}^{T_x} \rho c_p dT, \end{aligned} \quad (4)$$

where m denotes the element mass, $(\delta x, \delta y, \delta z)$ the element dimensions, ρ the mass density, and c_p the isobaric heat capacity.

During the same process, the energy loss by thermal conduction to its neighbor element is

$$\delta U_{cond} \approx \int_{t_0}^{t_x} q_{cond} \delta x \delta y dt = \delta x \delta y \int_{t_0}^{t_x} -\lambda \frac{\partial T}{\partial z} dt, \quad (5)$$

where $-\lambda \frac{\partial T}{\partial z}$ is the primary temperature gradient component. The energy transfer in the x direction is ignored, since the *net* contribution from $\partial T/\partial x$ is small.

Simultaneously, the energy loss by thermal convection to the nearby environment is

$$\begin{aligned} \delta U_{conv} &= \int_{t_0}^{t_x} \int_{\Gamma} q_{conv} dS dt \\ &\approx (2\delta x \delta z + \delta x \delta y) \int_{t_0}^{t_x} h(T(t) - T_{\infty}) dt, \end{aligned} \quad (6)$$

where Γ is the free surface of the element with an area of approximately $(2\delta x \delta z + \delta x \delta y)$, q_{conv} denotes the directional convective heat flux and is described by Newton's law of cooling $q_{conv} = h(T(t) - T_{\infty})$, $T(t)$ is the element temperature, and T_{∞} is the temperature of the far environment, which is assumed to be equal to the temperature of the nearby environment $T_{\infty} = T_a$.

For the same period, the energy loss by thermal radiation through the same free surface to the far environment is

$$\begin{aligned} \delta U_{rad} &= \int_{t_0}^{t_x} \int_{\Gamma} q_{rad} dS dt \\ &\approx (2\delta x \delta z + \delta x \delta y) \int_{t_0}^{t_x} \epsilon \sigma (T^4(t) - T_{\infty}^4) dt, \end{aligned} \quad (7)$$

Table II. Two future directions for FFF

	High resolution	High volume flow rate
Layer thickness, h	$< 10^2 \mu\text{m}$	$> 10^3 \mu\text{m}$
Volume flow rate	$< 10^0 \text{ cm}^3/\text{h}$	$> 10^3 \text{ cm}^3/\text{h}$
Typical Bi number	$\ll 0.1$. Thermally simple within a strand. Thermal conduction dominates the cooling	> 1 . Thermally complex within a strand. Thermal convection and radiation dominate the cooling
Component applications	Small, functional	Large, structural
Challenges	Bond quality, cooling too fast.	Gravity, efficiency, cooling too slowly

Fig. 2. (a) Cross-sectional morphology in FFF-printed double-wall and a demonstration of the heat transfer in element segment J21 before its intralayer reheating. (b) Temperature profiles of element J21 (blue) and its underlying neighbor J20 (green). t_0 is the deposition moment of J21; t_1 is its intralayer reheating moment; t_2 is its interlayer reheating moment, $t_2 = t_0 + \Delta\tau$, where $\Delta\tau$ is the interlayer time (Color figure online).

where $q_{rad} = \varepsilon\sigma(T^4(t) - T_\infty^4)$ is the radiant heat flux (temperature units of K), described by the Stefan-Boltzmann law of thermal radiation, ε is the emissivity, and $\sigma = 5.670 \times 10^{-8}$ W/m²/K⁴ the Stefan-Boltzmann constant.

Once the end time t_x is specified, the importance of each heat transfer mechanism $\delta U_{cond}/\delta U$, $\delta U_{conv}/\delta U$, and $\delta U_{rad}/\delta U$ can be obtained directly based on the ratios between Eqs. 5–7 and 4. However, the accuracy of such a calculation would depend heavily on the uncertainties in the geometry factors of the real bond width and the area of free surface Γ (Fig. 2a). To reduce such uncertainties, a relative approach is applied to calculate the contribution from each heat transfer mechanism during the cooling, expressing the energy lost by conduction and radiation as ratios of that by convection, i.e.,

$$\frac{\delta U_{cond}}{\delta U_{conv}} = \frac{\delta x \delta y \int_{t_0}^{t_x} -\lambda \frac{\partial T}{\partial z} dt}{(2\delta x \delta z + \delta x \delta y) \int_{t_0}^{t_x} h(T(t) - T_\infty) dt}, \quad (8)$$

$$\frac{\delta U_{rad}}{\delta U_{conv}} = \frac{\int_{t_0}^{t_x} \varepsilon \sigma (T^4(t) - T_\infty^4) dt}{\int_{t_0}^{t_x} h(T(t) - T_\infty) dt}. \quad (9)$$

Then, the significance of each heat transfer mechanism can be obtained by solving the linear Eqs. 3, 8 and 9.

In particular, the relative significance of radiation compared with convection, $\delta U_{rad}/\delta U_{conv}$, has no dependence on the geometry factors, thus Eq. 9 solely

depends on the specified temperature profile $T = T(t)$, $t \in [t_0, t_x]$, for a given material and process. Taking $t_x = t_0 + 1/2\Delta\tau$ in dataset 1, the experimental data (Fig. 1a, Exp.1) reveal $\delta U_{rad}/\delta U_{conv}$ to be 10%, indicating that radiant heat transfer is much less significant compared with forced convection in high-resolution printing. The simulation gave 11%, in good agreement with the calculation based on the experimental data. Taking $t_x = t_0 + \Delta\tau$ for the single wall, the experimental data in Fig. 1a (Exp.2, Exp.3) give $\delta U_{rad}/\delta U_{conv}$ of 186% and 118% for dataset 2 and 3, respectively; in either case, radiant heat transfer is more important than natural convection. The simulations confirm the relative significance to be 180% and 123%, respectively. For all three datasets, the calculations from the simulations agree well with the calculations from the experimental data.

Based on the good performance of the simulation results, Fig. 3a presents the pointwise contribution of $\delta U_{cond}/\delta U$, $\delta U_{conv}/\delta U$, and $\delta U_{rad}/\delta U$ in dataset 1 for all locations facing the $-y$ direction (3002 elements, excluding those on the edge), from their respective deposition moment t_0 to the characteristic time $t_x = t_0 + 1/2\Delta\tau$. For those locations, the primary thermal conduction takes place in the downward direction. In this example of high-resolution printing, $\delta U_{cond}/\delta U$ accounts for 52% of the energy loss on average, $\delta U_{conv}/\delta U$ accounts for 43%, and $\delta U_{rad}/\delta U$ accounts for the remaining 5%. For some locations, $\delta U_{cond}/\delta U$ even exceeds 60%. These results suggest that, even with forced convection, thermal conduction is the primary source of energy loss during the cooling, being dominance in the

Fig. 3. Pointwise contribution of three heat transfer mechanisms in the total energy loss during cooling: (a) dataset 1, $h = 300 \mu\text{m}$, $t \in [t_0, t_0 + 1/2\Delta\tau]$, (b) dataset 3, $h = 4064 \mu\text{m}$, $t \in [t_0, t_0 + \Delta\tau]$.

energy transfer. Considering the dependence of the conductive heat flux on the layer thickness (Eq. 1), the contribution from the conductive heat loss will become more significant when printing at even higher resolutions (lower layer thickness).

However, when the cooling is significantly slower, the significance of the three mechanisms in the energy loss differs. In dataset 3, when the volume flow rate is high, the significance of each heat transfer mechanism at 3354 locations was examined for the time period of $[t_0, t_0 + \Delta\tau]$. The contributions are presented in Fig. 3b. In this case, thermal convection and radiation collectively contribute $> 80\%$ of the energy loss, thus becoming the primary sources of energy loss. Thermal conduction accounts for only 18% of the energy loss within the interlayer time; this low significance also explains the disappearance of the reheating peak in Fig. 1a (Exp.3).

It is noteworthy that, when examining a different location, e.g., element P20 in Fig. 2a (where primary thermal conduction takes place in two directions), or switching to a different time interval, e.g., requiring $t \in \{t | t_0 \leq t \leq t_0 + 1/2\Delta\tau, T_{i,j,k} > T_{i,j,k-1}\}$ to ensure a unidirectional temperature gradient (Fig. 2b), will not fundamentally change the significance of each heat transfer mechanism during the cooling (although the contribution from conductive heat transfer will be higher). The same qualitative results remain valid: thermal conduction prevails the cooling in high-resolution printing, while thermal convection and radiation dominate the cooling when printing at a high volume flow rate.

Fig. 4. Local ($r = (9,0,6) \text{ mm}$) temporal temperature profile of FFF on the Moon, in contrast to similar processes on Earth (Sim.1-1, forced convection; Sim.1-2, natural convection).

Simulating FFF on the Moon

According to this analysis, thermal convection plays a critical role in part cooling at high volume flow rates. However, since it completely disappears on the Moon, printing of large, structural components with high layer thicknesses becomes doubtful: the deposited parts may fail to cool fast enough to withstand the dragging disturbance or self-weight. However, the avenue to apply FFF for precision manufacturing at high resolution remains open.

If the printing job in dataset 1 is to be performed on the Moon, its simulation essentially requires a null convective heat transfer coefficient, i.e. $h = 0 \text{ W/m}^2\text{K}$ and an ambient temperature $T_\infty = -20^\circ\text{C}$. All the other parameters agree with those in Table I. The temporal temperature profile at $r = (9,0,6) \text{ mm}$ is shown in Fig. 4, in contrast to the counterpart printing on Earth (Sim.1-1 at forced convection, $h = 60 \text{ W/m}^2\text{K}$, $T_\infty = 21.2^\circ\text{C}$; Sim.1-2 at natural convection, $h = 8.5 \text{ W/m}^2\text{K}$, $T_\infty = 21.2^\circ\text{C}$).

Intuitively, the reduced convection when printing on the Moon would lead to a drop in the cooling rates. However, the colder ambient environment somewhat compensates for this as the radiant heat flux will be higher (by 5% at the deposition temperature). The overall cooling is only slightly slower than when printing on Earth subject to natural convection: the maximum temperature difference in the temporal profiles given by the $\|\bullet\|_\infty$ norm

$$\|\bullet\|_\infty = \max_{t_0 \leq t \leq t_0 + 1/2\Delta\tau} |T_{\text{Moon}} - T_{\text{Sim.1-2}}| \quad (10)$$

is only 6.2°C . Due to the overall similarity in the local temporal temperature profiles, the physical process of Sim.1-2 was carried out on Earth. Compared with Exp.1 (Table I), the part cooling fan was disabled. The printing turned out to be a limiting case in FFF that can still cool fast enough to form a rigid object. However, any attempts to considerably delay the cooling (e.g., by increasing the speed/layer thickness) may cause the printing to fail. Hence, the profile in Fig. 4 suggests that FFF on the Moon could potentially cool fast enough to form a rigid object during printing. Nevertheless, if the printing

Fig. 5. Comparison of temperature field $T(x, 0, z, t)$ between FFF on the Moon and printing on Earth subject to natural convection. Two characteristic time spots are chosen: t_N denotes the time when FFF is finished; $2t_N$ is a time indicating the steady state.

succeeds under forced convection but fails under natural convection on Earth, it will also fail on the Moon. These analyses indicate that the process window for FFF on the Moon is narrower. To guarantee successful printing of dataset 1 on the Moon, the nozzle travel speed can be slowed down to ensure a longer interlayer time, or a smaller layer thickness could be used such that the temperature is lower before interlayer reheating.²⁷ However, either solution would lead to a lower volume flow rate during printing and lower manufacturing efficiency¹¹ than counterpart printing on Earth.

Besides, Fig. 4 also presents a pseudo process where only thermal conduction occurs ($h = 0$ W/m²/K, $\varepsilon = 0$, dashed line). Such a process has no chance to succeed, as the PLA material has a melting temperature of $\sim 155^\circ\text{C}$. However, it manifests the importance of radiant heat transfer during part cooling on the Moon.

Apart from the temporal temperature profiles, more results on the temperature fields $T(x, 0, z, t)$ are compared in Fig. 5, to shed light on the process limit of FFF on the Moon. For the temperature fields in Exp.1-2 (the same as in dataset 1, but with natural convection), at $t = t_N$ upon finishing, the top few layers remain hotter than the rest, and the fields show a strong dependence on location. At steady state (e.g., $t = 2t_N$), the temperature decreases from the

bottom at the plate temperature toward the top at the ambient temperature, with a negligible gradient in the x direction. However, if printing on the Moon, the simulations reveal that the temperature gradient in the printed parts is significantly higher than the counterparts on Earth (Fig. 5). The gradient component in the z direction almost doubles everywhere at both characteristic times (t_N and $2t_N$); the gradient component in the x direction is also more noticeable. These observations suggest that the thermal stress and consequent warpage, delamination, etc., in FFF could be even more problematic on the Moon, particularly when printing large objects or structural components. Thus, FFF on the Moon is more suitable for printing small or functional components, such as oxygen generation adapters, antenna feed-horns,² personalized pharmaceutical dosage forms with tailored performance,^{28,29} etc.

FFF on Mars

This analysis of FFF on the Moon can naturally be extended to printing on Mars, where the Martian surface pressure is on the magnitude of 10^2 Pa, and the average ambient temperature is around -65°C .¹⁴ The convection coefficient is estimated to be on the magnitude of 10^0 W/m²/K.¹⁶ Interested readers can use the T4F³ model in Ref. 19 to explore the possibility of FFF on the Mars on their own.

CONCLUSION

This article analyzes the heat transfer mechanisms during fused filament fabrication (FFF) at different resolutions. Experimental data and simulations reveal that thermal conduction prevails in the part cooling when printing at high resolution (low layer thickness), while thermal convection and radiation dominate the part cooling when printing at high volume flow rate (high layer thickness). A preliminary analysis of the possibility of FFF on the Moon is performed by analyzing the cooling profiles in parts printed at high resolution. The natural environment on the Moon is challenging for FFF as the ultrahigh vacuum will completely disable thermal convection. Nevertheless, at the lower lunar ambient environment temperature, cooling of the printed part should be only slightly slower than when counterpart printing on Earth subjected to natural convection. The results indicate that it is still possible to perform FFF in the natural environment on the Moon, although the process window will be narrower and the efficiency lower. In addition, the temperature gradients and thermal stress will be higher, making the use of FFF more suitable for precision manufacturing of small or functional components.

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CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there are no conflicts of interest.

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