Liquid Metal Printing

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1 Scrap aluminum melting.

ABSTRACT

Additive manufacturing (AM) is often cited as a sustainable alternative to conventional manufacturing, offering material efficiency through free complexity, reducing scrap and capturing waste streams. Indeed, AM has permeated a variety of material processes from polymers to ceramics. However, the landscape of metal additive techniques has been limited by challenges in scalability, and its application has tended toward high-cost-per-volume parts for aerospace and automotive industries. Nevertheless, worldwide production of metal parts, specifically steel and aluminum, is among the most energy intensive of any material produced today. Within architecture and construction, welding arc additive manufacturing is one of the only metal additive techniques with the ability to produce large-scale parts, although this process, too, is limited by slow print speeds.

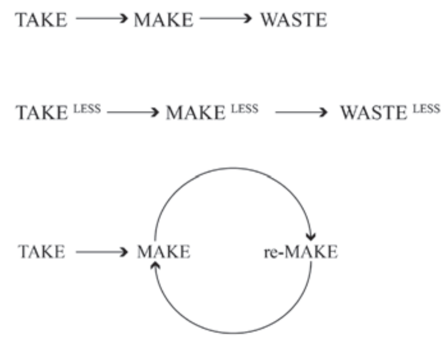
In this research paper, we present liquid metal printing (LMP), a novel metal additive technique that trades high resolution to achieve fast, scalable, and low-cost printing. Liquid metal printing is conceptually similar to free-form-casting, where a large amount of metal is melted and rapidly dispensed along a predefined toolpath in order to produce a 3D form. To explore the capabilities of LMP, we develop purpose-built hardware to rapidly print aluminum, a material chosen for its ubiquity and near infinite recycle-ability. Furthermore, we assess the feasibility of LMP as a sustainable prototyping tool in product design by rapidly printing furniture-scale parts. These case studies in furniture prototyping demonstrate LMP as a paradigm-shifting approach to enable metal printing in architecture and construction.

INTRODUCTION

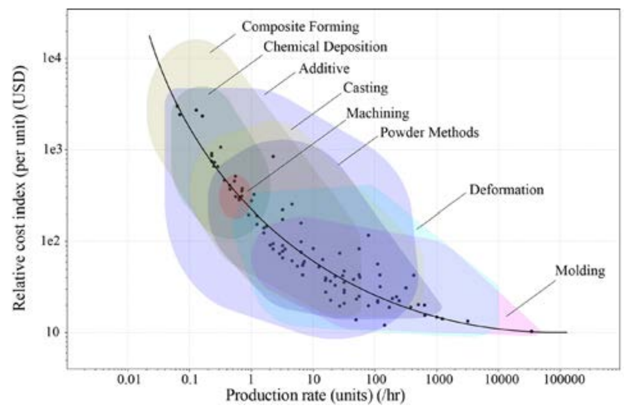
The building sector accounts for roughly one third of global energy and process emissions (CDB 2022). Among the materials produced in excess of one million tons per year, the vast majority are used for structural purposes, including concrete, steel, and aluminum. Hence, the lifetime of a material needs substantial consideration, and aluminum, in particular, offers a path toward circular manufacturing due to potentially high metal retention between casting and re-casting in its recycling (Altenpohl 1998).

The conventional approach to fabrication follows a linear path of using virgin material, manufacturing the material into a product with a finite service life, after which the product becomes waste (Figure 2). Taking less, making less, and wasting less involve strategies of material efficiency enabled by advanced computational methods like topology optimization. The aerospace and automotive industry is replete with parts where the buy-to-fly ratio is significant, typically 20:1, referring to the ratio of the mass of the stock material to the mass of the finished part and, hence, the amount of material lost as scrap. The decision to reduce entire billets of material to chips comes at significant material cost, especially with virgin material. Hence the "Take, Make and Re-make" strategy describes the reuse of material, reducing the embodied energy of the final part. Virgin aluminum, for example, has an embodied energy of 270 megajoules per kilogram (MJ/kg), but it can be recycled for less than 10 percent of its initial processing energy (Altenpohl 1982; Otis 2014).

An emerging alternative that captures both material efficiency and circular production is AM, especially with metal materials used to make high-performance parts that would be difficult or impossible to produce with conventional manufacturing techniques (Agrawal and Vinodh 2019). However, the current state of metal additive techniques comes with significant processing cost, reduced production rates, and build environments that are challenging to scale (Armstrong, Mehrabi, and Naveed 2022). To address these shortcomings, we propose a novel manufacturing process called liquid metal printing (LMP). This metal additive technique involves the rapid deposition of molten material (Figure 1) into a bed of granular media along a predefined toolpath. Similar approaches have been attempted at small scale on a heated substrate, including direct metal writing (Chen et al. 2017) or drop on demand printing (Ansell 2021). While these approaches have targeted small-scale, high-resolution parts, we propose a new paradigm of rapid metal printing suitable for architecture and construction that achieves large-scale parts with coarse resolution without sacrificing high process rates. A description of the hardware design and underlying process physics will be presented in this paper. Further, a series of geometric experiments have been undertaken to demonstrate the potential of LMP as a fast and scalable alternative to conventional metal additive techniques.



2 Approaches to material utilization.

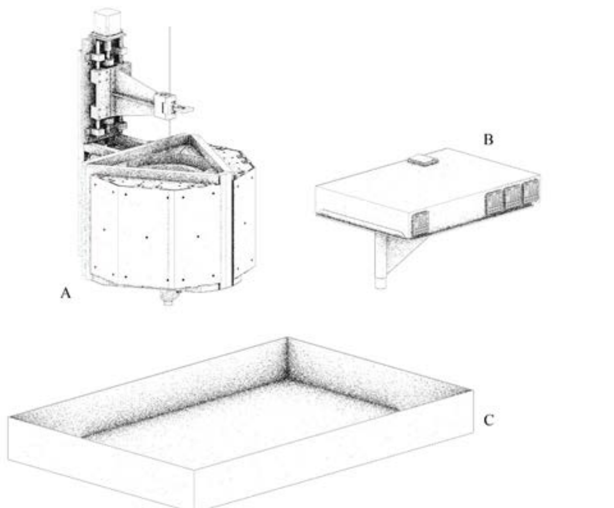


3 Manufacturing production and cost.

BACKGROUND

There is a plethora of metal additive techniques, commonly classified into four main types by American Society for Testing and Materials (ASTM). These are material extrusion, binder jetting, powder bed fusion, and direct energy deposition (Armstrong, Mehrabi, and Naveed 2022). Each method bears consequences to energy consumption, process rate, resolution, scale, performance, and cost.

Material extrusion is similar to fused deposition modeling (FDM) involving the heating of a filament, or pellet-based feedstock, typically a polymer-based binder impregnated with metal particles. In a post-processing step, the printed part undergoes debinding and sintering, leaving a near fully dense metal part (Ramazani and Kami 2022). Binder jetting involves the deposition of droplets of molten material onto a substrate similar to typical inkjet printing. These processes can be extremely fast, especially with the use of



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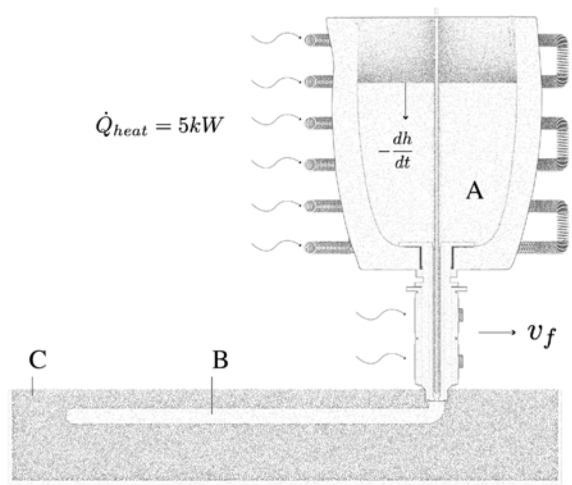

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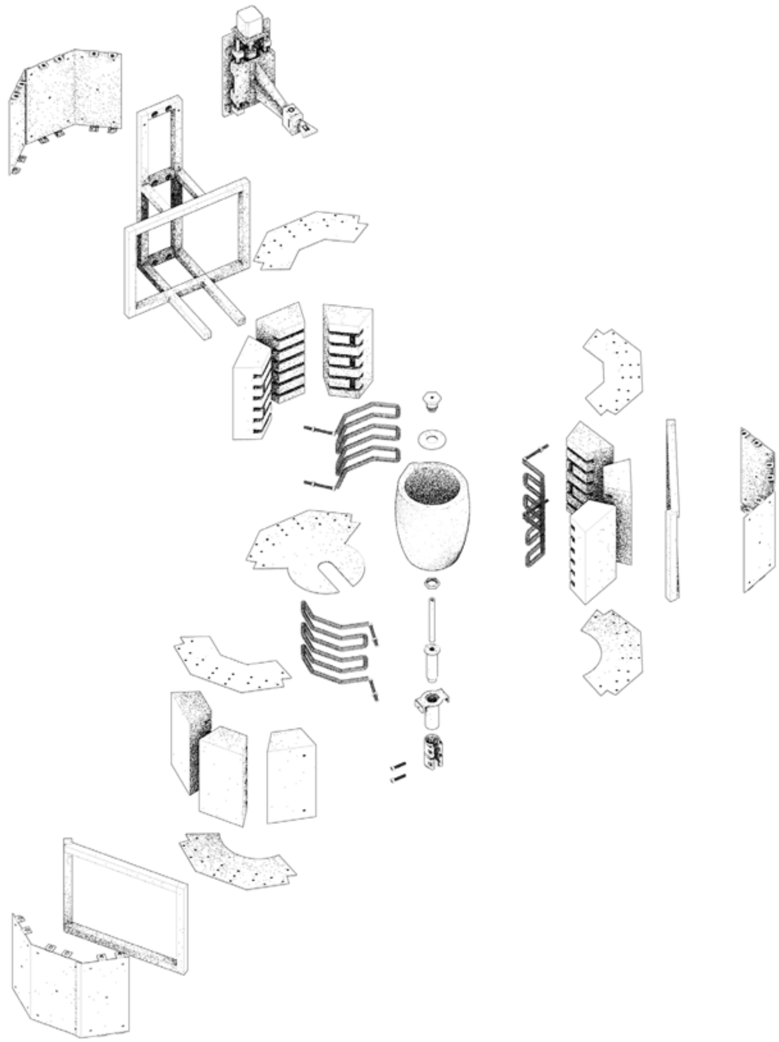
multiple printheads. Powder bed fusion involves selectively melting metal powder with a fiber optic laser or electron beam in an inert environment, building a part layer by layer. Direct energy deposition involves the melting of a wire or powder during deposition itself, such as in welding arc additive manufacturing (WAAM).

With the exception of WAAM, metal additive techniques are generally used for small-to-medium-scale parts with high resolution and cost. Thus, while additive manufacturing of concrete and thermoplastics has been developed at scale, the large-scale manufacture of metal components remains relatively limited. There are several reasons that have inhibited the adoption of metal additive manufacturing in lower-cost-per-volume industries, compared with additive manufacturing of thermoplastic polymers. Amongst all metal additive techniques, the process rate is orders of magnitude slower than conventional manufacturing due, in part, to the economies of scale afforded by parallel processes like injection molding or metal stamping ("Ansys® Granta Selector 2023 R1," n.d.) shown in Figure 3.

For metal additive manufacturing to become a viable technique for lower-cost-per-volume industries, like architecture and construction, slow process rate and high relative cost need to be challenged by reconsidering resolution. There is indeed a tension, described by Gutowski, between process rate and resolution, which is challenged with large-scale, polymer-based, additive manufacturing, typically called big area additive manufacturing (BAAM). By adopting a coarser resolution, greater efficiencies in energy consumption and process rate can be achieved, such that the specific energy intensities of BAAM become comparable to conventional manufacturing techniques like injection molding (Gutowski et al. 2017).

The same opportunities for metal additive manufacturing exist and are demonstrated in part by WAAM. Indeed, faster process rates and easier scalability make WAAM more amenable to experimentation in architecture and construction, as evidenced by large-scale building experiments by Arup and MX3D in the fabrication of a bridge (Buchanan and Gardner 2019). The alternative to large-scale metal AM components, involves printing intricate joints or nodes as demonstrated in the Nematox façade node (Emmer Pfenninger Partner AG, Strauß, and Knaack 2016) or Arup's topology optimized lighting node (Galjaard, Hofman, and Ren 2015). Furthermore, the coupling of metal additive manufacturing techniques, most commonly direct energy deposition methods, with selective machining of sensitive features, also known as hybrid manufacturing, has been demonstrated from medical application to aerospace parts (Armstrong, Mehrabi, and Naveed 2022). While WAAM has demonstrated experiments in the fabrication of large-scale structural components, there remain challenges to performance and process. Despite the higher process rates possible with WAAM, compared to other metal additive techniques, conventional manufacturing is still roughly 10 to 100 times faster. Furthermore, the presence of residual stress, due to the complex thermal history of melting and remelting portions of the print, may lead to failure modes like cracking or excessive warping (Hoye et al. 2014).

To overcome the present limitations amongst the raft of metal additive techniques, we propose LMP, a scalable and cost-effective technology to rapidly print structural components. Liquid metal printing offers a new paradigm of metal printing in architecture by shifting from small, slow, and fine resolution components, to large, fast, and medium resolution structural members.



4 LMP system components (A) Furnace (B) Temperature controller (C) Print bed.

5 Process schematic (A) Crucible (B) Printed bead (C) Granular media.

6 Furnace assembly.

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METHODS

Liquid metal printing is a rapid metal additive technique similar conceptually to free-form casting, where in the absence of a pattern or formwork, molten material is dispensed along a predefined toolpath describing a 3D form. The LMP system consists of three parts illustrated in Figure 4, the furnace and nozzle assembly, the print bed, and temperature controller. Metal feedstock, in this case scrap aluminum sourced locally from waste material in various machine shops, is melted in the furnace and deposited rapidly in a print bed of granular media. The granular media, 100 micron glass bead, acts as neutral suspension of molten material throughout the printing process. The temperature controller maintains precise control of the metal temperature from the furnace to the nozzle tip. For the experiments in this paper, the set point temperature is held at 700°C, slightly above aluminum's melting point of 660°C.

Molten material is held in a crucible (Figure 5A), which is subject to roughly 5kW of power, sufficient to heat and melt a significant volume of aluminum rapidly. The system is gravity driven, such that the pressure head of molten metal in the crucible initiates volume flux at the nozzle tip, resulting in a bead of printed metal (Figure 5B) in the bed of granular media (Figure 5C) at a feed-rate denoted by v_f. A plug rod is used to control the flow rate at the nozzle; nevertheless, the crucible melt height, print depth, nozzle geometry, and feed rate have profound impacts on the resulting bead diameter and print geometry.

Furnace Assembly

The source of heat is integral to any metal additive process. Liquid metal printing uses a custom-built 5kW furnace capable of holding a No. 10 graphite crucible. This furnace uses 1/16-inch-thick nichrome wire coiled on a lathe and fitted into refractory brick. Three resistive heating coils each dispense up to 1.75kW, enabling the rapid melting of material. Additional insulation helps reduce the melting time, and improve the efficiency of the furnace. The furnace takes the form of a nine-sided polygon, two-thirds of which are mounted on hinges that allow the furnace to

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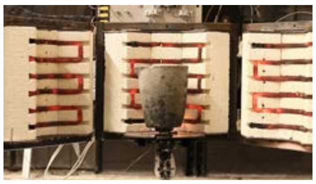

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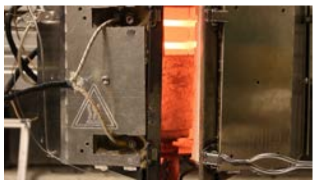

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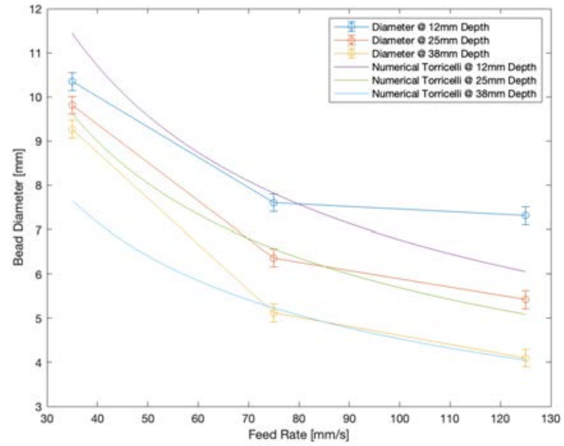

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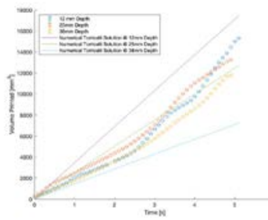

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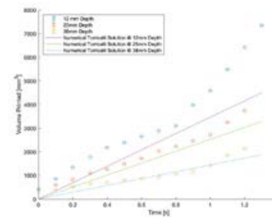

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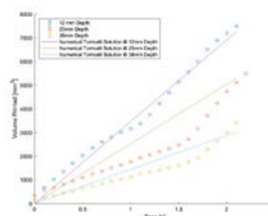

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7 Machining of a graphite crucible.

8 Stainless-steel coupling.

9 High-strength alumina ceramic nozzle shaft inserted in the stainless-steel coupling, and adhered with zirconia paste.

10 Installing the nozzle assembly in the furnace.

11 Furnace doors open, showing coils at high temperature.

12 Furnace doors closing.

13 Printed bead experiments with numerical Torricelli solution.

14 Volume flux prediction at 35mm/s.

15 Volume flux prediction at 75mm/s.

16 Volume flux prediction at 125mm/s.

17 Printed specimens at different feed rates.

open and close for the maintenance of the crucible and nozzle (Figure 6, Figures 10 through 12).

The furnace needed to be light enough to be mounted to the Z axis of a conventional computer numerical control (CNC) router, and move at roughly 150mm/s without stalling the X and Y axis motors. Hence, the furnace is made as tight as possible to fit the crucible geometry. High temperature K-Type thermocouples are fixed to the base of each third of the furnace and serve as inputs to a proportional-integral-derivative (PID) controller.

Nozzle Assembly

The nozzle assembly includes the crucible, nozzle shaft, and additional heating elements. One of the key challenges to LMP and, indeed, any additive process in which molten metal is held and dispensed through a nozzle, such as in binder jet printing, is the corrosion resistance required of all mechanical components (Li et al. 2020). The crucible used here is a clay graphite refractory material common to foundry applications. The crucible is machined on a lathe (Figure 7), and a stainless-steel coupling (Figure 8) is used to connect the nozzle outflow shaft to the crucible (Figure 9). While molten aluminum readily corrodes thin stainless-steel parts, if made with sufficient thickness in excess of 1/8 inch, stainless steel acts as an acceptable interface between ceramic components. In fact, aluminum readily adheres to stainless steel, making the coupling watertight despite its loose fitting to the crucible.

A zirconia ceramic adhesive is used to affix the nozzle outflow shaft, an alumina tube, to the stainless-steel coupling. This subassembly sleeves into the furnace shown in Figure 10. The nozzle outflow shaft is further lined with 350-watt band heaters capable of maintaining roughly 600°C at the nozzle tip. These components are sufficiently corrosion resistant, and can withstand temperatures of up to 1,100°C for sustained periods of time.

Process Parameters

The bead diameter and, hence, resolution of LMP is tied to several parameters, including the diameter of the nozzle,



18 XY plane double bead.

19 YZ plane double bead.

20 YZ + XY plane triple bead.



21 XY plane spiral.

22 XY plane zig zag.

23 Spiral helix.

the pressure head of molten metal in the crucible, the print depth, and the feed rate. A matrix of experiments across print depth and feed rate have been undertaken to validate a numerical solution for bead diameter, derived from an energy head equation and a mass continuity equation. The specimens were 3D scanned to extract time-based volumetric and cross-sectional data. The print beads show oscillation in cross-sectional area (Figure 17), evidence of Rayleigh instability, the tendency of fluid streams to form droplets due to surface tension, and, in LMP, as a consequence of the friction between the molten aluminum flowing out of the nozzle and the nozzle surface itself (Lemons, Lipsombe, and Faehl 2022). The numerical solution takes the form of a first-order, non-linear, differential equation, a variation of the Torricelli solution, which models fluid flow out of a cylindrical vessel (White 1979). For a given printing scenario and process window of feed rate and print depth, our numerical solution can predict a resultant bead diameter (Figures 13 through 16). The current model is validated against feed rate and print depth, and after further experimentation with different nozzle configurations, the model appears to generalize to adequately describe different printing scenarios and nozzle geometries. Furthermore, this numerical model could be used to simulate prints, as well as inform toolpath automation and printing procedure. For example, the greatest volume flux occurs at the beginning of a print, tapering off gradually until no material is left in the crucible. Hence, the features that need larger diameter cross-sections are typically printed first, with thinner features printed towards the end of the toolpath. Additionally, the depth of the print can be tuned to maintain bead thickness, especially at the end of a toolpath. Hence, these degrees of freedom, while manually adjusted in the current iteration of the work, could be automated, and more rigorously optimized to match a target geometry.

Geometric Experiments

More complex toolpath experiments have been conducted, extending the intuition gained from printing straight line specimens. Several bead overlapping experiments were undertaken to explore the potentials for bonding molten aluminum over distance. With sufficient volume flux at the nozzle tip, it was possible to print double and triple bead geometries. Overlapping strategies have been employed in the XY, YZ and XY, and YZ planes to produce different thickness printed beads (Figure 18 through 20). The beads printed measure roughly eight inches long, and range from 3/4 inch to 1.5 inch in thickness, demonstrating the potential to print sizeable cross-sections with structural capacity. Furthermore, the specimens printed here take roughly 10 seconds to execute, given a feed rate of 50mm/s.

Further experiments in surface-based toolpaths (Figure 21 through 23) show the challenges of LMP to produce surfaces as both solidification and formation of an oxide layer on the surface of molten aluminum, prevent bonding over distance. Overlapping in the XY plane generally does not lead to bonding unless the volume flux is significant. Bonding over the Z axis, for example, through spatial printing yields more consistent bonds. Hence, more complex toolpaths exploit the Z dimension to achieve bonding, a strategy which is used in subsequent experiments to print variably thick parts. Printing variable thickness permits the ability to tune structural performance and, hence, develop materially efficient parts.

Finally, larger, and more complex toolpaths were tested to extend the overlapping strategies in the previous experiments (Figures 24, 25). Here, a series of frames were printed to demonstrate the ability to print at scale, and test the coupling of LMP with selective post-machining. The printed frames attempted to incorporate the strategies of oblique bead overlapping to generate variable thickness. The frames printed were sufficient in cross-section to withstand machining. The irregular frame was post-machined on a knee mill, demonstrating the ability of the printed part to be precision bored or to accept threads and assembled as part of a larger structure. The process of post machining is shown in Figures 26 and 27.

As a final demonstration, a chair prototype (Figures 28 and 29) was fabricated by employing oblique overlapping toolpaths to achieve thickness in structurally sensitive areas (Figure 30), and strategic post machining to support joinery. The printed aluminum frames are machined with two dado features to receive a maple seat and back. Matching slots, undersized by 0.005 inch are cut into the maple parts using a CNC router.

RESULTS AND DISCUSSION

Liquid metal printing, a novel metal additive technique, offers an alternative to the paradigm of high resolution and slow process rate. This manufacturing strategy trades resolution for speed and scale, appropriate for large structural components typical of construction, architecture, and industrial design. A series of geometric experiments demonstrate the feasibility of LMP to produce large-scale parts in a matter of seconds, and a numerical solution is derived based on the underlying process physics of LMP in order to predict print output. Aluminum has been chosen as a ubiquitous and nearly infinitely recycle-able material. The embodied energy of aluminum is significant, and the virgin material is costly. Its value comes in the form of an energy bank, wherein initially high energy input is rewarded by energy savings due to its light weight, an advantage especially felt in vehicular applications (Altenpohl 1998) . However, the reuse of aluminum, too, can be sustainable, as recycling aluminum requires less than 10 percent of its primary production embodied energy (Otis 2014). The potential of rapid prototyping using scrap

24 Square frame.

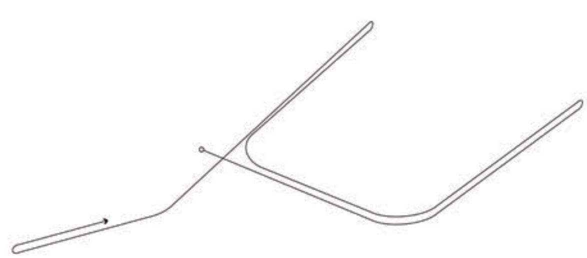
25 Irregular frame.

26 Precision boring.

27 Thread milling.

28 Chair frame.

29 Assembled chair.



30 Chair frame

31 Furniture

material is demonstrated through the geometric experiments shown in this paper. Scrap material in different forms was sourced from various machine shops, from lathe cutoffs to aluminum extrusions (Figure 1). Melt times varied with the ratio of surface area to volume of the scrap material; for example, aluminum extrusions melted extremely quickly. When recycling aluminum, several strategies can be employed to maximize metal retention and maintain the concentration of alloying materials. The addition of alloying elements, or printing with multiple metal materials held in separate crucibles, is the subject of further research. The potential of printing multi-material metal parts with varying performance, at large scale, could have profound impacts on architecture and construction by adding a material dimension to geometrically optimized structure.

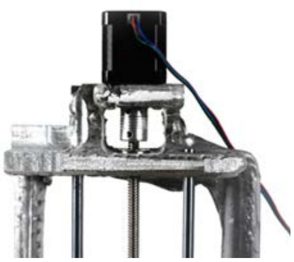
The current coarse resolution output by the LMP process is comparable to WAAM, where both processes require strategic post machining. Nevertheless, LMP proves at least 10 times faster and with more efficient heating, could potentially reach process rates exceeding tens of kg/hour, approaching the process rate of injection molding or die casting, at roughly 100kg/hour. One of the advantages of LMP over alternative metal additive methods is the singular thermal cycle of a print. Unlike WAAM, which involves successive melting and cooling of the workpiece to maintain its structure, the granular media used in LMP supports the molten material throughout the print. Further, the limitations to print speed in powder bed fusion or direct energy deposition are a consequence of the transition from melting to vaporization (Ion, Shercliff, and Ashby 1992). In LMP however, the faster the material is deposited, the less likely inclusions from oxidation will form.

Further experimentation around nozzle orifice diameter will be undertaken to refine the numerical model and develop finer control. Currently, the hydraulic diameter and crucible melt volume are extremely sensitive parameters. With larger nozzle diameters, the metal flow at the nozzle tip enters the turbulent flow regime leading to highly irregular, extremely large cross-sections that are one to two inches in diameter. Furthermore, surface wetting of the nozzle occurs despite the use of alumina at the nozzle tip. The tenacity of the aluminum to cling to the nozzle has detrimental effects on the quality of toolpaths with multiple overlaps. Finally, the oxidation layer that forms during printing must be prevented to ensure that bonding can occur without interruption, which could be achieved with a shroud of inert gas.

32 Circular boring.

33 Right angle milling.

34 Lead screw feature.



35 Linear actuator.

The case studies in geometry and product design demonstrate LMP as a rapid prototyping tool for metal components. Earlier investigations into metal printing led to the products depicted in Figure 31. These chairs show the potential of LMP to quickly explore topologies of structure at scale. Each print took no longer than one minute to produce, with various strategies of joinery.

The potential of LMP as a prototyping tool in mechanical design has been explored, but will be the subject of further research. Figures 32 through 35 show mechanical parts that were printed with LMP. Precision features are machined into these parts to accept bearings, provide clearance for a lead screw (Figure 34), and act as a frame for a linear actuator (Figure 35). The coupling of coarse resolution with precision machining (Figures 32 and 33) offers a sustainable alternative to the slow, energy intensive, and costly landscape of existing metal additive techniques. With advanced fabrication methods enabled by 3D scanning, feature detection, and multi-axis machining, coarse resolution, rapidly printed parts can be made to fit in complex assemblies.

CONCLUSION

A novel metal additive manufacturing technique called Liquid metal printing has been introduced, the design and functionality of the machine has been described, and the printed outputs have been characterized. We propose this process as an alternative approach to conventional metal printing that favors high resolution at the expense of high energy consumption, slow process rates, and high material cost. Instead, LMP is a coarse resolution, rapid, cost-effective, and scalable metal printing process more suited to large-scale components for product design or architectural assemblies. Coupled with precision machining in a hybrid manufacturing process, LMP has demonstrated the ability to produce large-scale parts capable of fitting into larger assemblies. Through a series of geometric case studies, we show strategies for printing with variable thickness in order to produce structural parts. Further, a numerical simulation predicting print geometry from specific process parameters has been developed, and will be refined in future work.

While the coupling of LMP with subtractive machining has been demonstrated, other processes like bending and forming may be employed to yield new hybrid manufacturing techniques. These are demonstrated by several chair prototypes shown in Figure 31, which were bent into shape. Further work will explore other kinds of hybrid manufacturing, for example, forming and stamping, and the new application spaces opened by them.

In conclusion, we demonstrate that LMP holds the potential to become a productive force in the landscape of manufacturing and design, both as a tool for prototyping, and as a form of rapid, low-cost, large-scale, circular production.

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REFERENCES

Agrawal, Rohit, and Sekar Vinodh. 2019. “State of Art Review on Sustainable Additive Manufacturing.” Rapid Prototyping Journal 25 (6): 1045–60. https://doi.org/10.1108/RPJ-04-2018-0085.

Altenpohl, Dietrich. 1982. Aluminum Viewed from Within. Dusseldorf: Aluminum-Verlag.

Altenpohl, Dietrich. 1998. Aluminum: Technology, Application, and Environment. 6th ed. The Minerals and Metals Society.

Ansell, Troy Y. 2021. “Current Status of Liquid Metal Printing.” Journal of Manufacturing and Materials Processing 5 (2): 31. https://doi.org/10.3390/jmmp5020031.

“Ansys® Granta Selector 2023 R1.” n.d. Ansys.

Armstrong, Mark, Hamid Mehrabi, and Nida Naveed. 2022. "An Overview of Modern Metal Additive Manufacturing Technology." Journal of Manufacturing Processes 84 (December): 1001–29. https://doi.org/10.1016/j.jmapro.2022.10.060.

Buchanan, Craig, and Leroy Gardner. 2019. "Metal 3D Printing in Construction: A Review of Methods, Research, Applications, Opportunities and Challenges." Engineering Structures 180 (February): 332–48. https://doi.org/10.1016/j.engstruct.2018.11.045.

CDB, Penrose. 2022. "2022 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION."

Chen, Wen, Luke Thornley, Hannah G. Coe, Samuel J. Tonneslan, John J. Vericella, Cheng Zhu, Eric B. Duoss, Ryan M. Hunt, Michael J. Wight, Diran Apelian, Andrew J. Pascall, Joshua D. Kuntz, and Christopher M. Spadaccini. "Direct Metal Writing: Controlling the Rheology through Microstructure." Applied Physics Letters 110, no. 9 (February 27, 2017): 094104. https://doi.org/10.1063/1.4977555.

Emmer Pfenninger Partner AG, Holger Strauß, and Ulrich Knaack. 2016. "Additive Manufacturing for Future Facades: The Potential of 3D Printed Parts for the Building Envelope." Journal of Facade Design and Engineering 3 (3–4): 225–35. https://doi.org/10.3233/FDE-150042.

Galjaard, Salomé, Sander Hofman, and Shibo Ren. 2015. "New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing." In Advances in Architectural Geometry 2014, edited by Philippe Block, Jan Knippers, Niloy J. Mitra, and Wenping Wang, 79–93. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-11418-7_6.

Gutowski, Timothy, Sheng Jiang, Daniel Cooper, Gero Corman, Michael Hausmann, Jan-Anders Manson, Timo Schudeleit, Konrad Wegener, Matias Sabelle, Jorge Ramos-Grez, and Dusan P. Sekulic. 2017. "Note on the Rate and Energy Efficiency Limits for Additive Manufacturing: Rate and Energy Efficiency Limits for AM." Journal of Industrial Ecology 21 (S1): S69–79. https://doi.org/10.1111/jiec.12664.

Hoye, Nicholas, Hui Jun Li, Dominic Cuiuri, and Anna M. Paradowska. 2014. "Measurement of Residual Stresses in Titanium Aerospace Components Formed via Additive Manufacturing." Materials Science Forum 777 (February): 124–29. https://doi.org/10.4028/www.scientific.net/MSF.777.124.

Ion, John C., Hugh R. Shercliff, and Michael F. Ashby. 1992. "Diagrams for Laser Materials Processing." Acta Metallurgica et Materialia 40 (7): 1539–51. https://doi.org/10.1016/0956-7151(92)90097-X.

Lemons, Don S., Trevor C. Lipsombe, and Rickey J. Faehl. 2022. "Vertical Quasistatic Poiseuille Flow: Theory and Experiment." American Journal of Physics 90 (1): 59–63. https://doi.org/10.1119/10.0006245.

Li, Ming, Wenchao Du, Alaa Elwany, Zhijian Pei, and Chao Ma. 2020. "Metal Binder Jetting Additive Manufacturing: A Literature Review." Journal of Manufacturing Science and Engineering 142 (9): 090801. https://doi.org/10.1115/1.4047430.

Otis, Paul. 2014. "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." Government Archive. Today In Energy. May 9, 2014.

Ramazani, Haidar, and Abdolvahed Kami. 2022. "Metal FDM, a New Extrusion-Based Additive Manufacturing Technology for Manufacturing of Metallic Parts: A Review." Progress in Additive Manufacturing 7 (4): 609–26. https://doi.org/10.1007/s40964-021-00250-x.

White, Frank. 1979. Fluid Mechanics. McGraw-Hill Book Company.

IMAGE CREDITS

All drawings and images by the authors.

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